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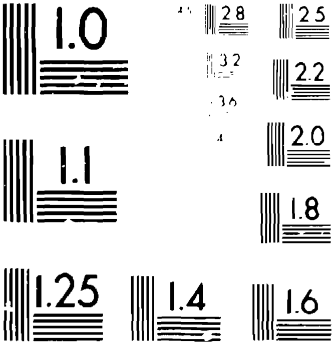

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WELDING PROCESSES AND APPLICATIONS

FUTURE TRENDS

(RESISTANCE, ELECTRON BEAM AND LASER WELDING)*

by

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1.0 INTRODUCTION

Electron Beam Welding is the process in which the heat required to produce fusion welds is obtained from the impact of a high velocity, high density stream of electrons on the workpiece. Upon impact the Kinetic energy of the electrons is converted to thermal energy causing both vaporization and melting (Refer Fig.1).

The vaporization of material immediately beneath the beam enables the beam to penetrate into or through the material to be welded, with the beam and vapour forming a hole. As the beam moves along the joint face, the molten material flows round the hole leaving the welded joint in the wake of the beam (Refer Fig.2).

EB welds have depth to width ratio of more than 10:1 due to the extremely high heat concentration. The beam is very narrow (less than 0.25 mm dia) and the welding speed is high. The net heat input is very low and the weld has parallel sides.

2.0 PRINCIPLE (refer Fig. 3)

2.1 Electron Emission:

The emitter is cathode - anode system raised to a very high potential in high vacuum.

2.1.1 Cathode:

It is made of tantalum or tungsten and heated either by Joule's effect directly or indirectly to about 4600 °F. At a high temperature thermoionic effect creates an electron cloud near its surface.

2.1.2 Anode:

The electric field between cathode and anode accelerates the electrons and sets them free with a considerable energy. The electrons pass through the anode and flow towards the part to be welded.

2.1.3 Wehnelt (Grid):

It is a metallic shield around the electron cloud, which is biased negatively in relation to cathode. It functions as an electric field shaper and plays the main part in the electron flow regulation, by forcing the equipotential lines to constrict the electron cloud. Geometry of the beam (Fig. 4a).

The geometry of the beam is controlled by using magnetic lenses, which focus the beam on the work piece. The focusing coil is supplied with high voltage for a perfect stabilization of the position of the focal spot.

2.1.4 Deflection (Refer Fig.5)

Magnetic coils are also used for obtaining beam deflection and manipulation of the beam spot on workpieces. Planer shapes can be generated on the workpiece surface, for controller welding by suitably adjusting the deflection fields. Deflection coils can also be used for linear movement of the beam.

2.2 Equipment Set-up (Refer Fig.6):

The welding gun can be either movable or fixed type. The welding chamber is provided with rotating and stationary fixtures and also with linear motion capabilities depending on the job requirement.

The gun is fed by electric, electronic, and control unit. Controls for varying beam current and accelerating voltage are done through these controls. Primary and secondary pumping systems are connected to the gun and chamber to provide the required vacuum.

Control for beam oscillation, beam spinning, focusing are provided in the control unit. Precision speed control for gun carrier and job movement are also provided in the same panel.

3.0 PROCESS VARIABLES AND THEIR INFLUENCE IN EBW

3.1 Accelerating Voltage:

The importance of the accelerating voltage lies in its ability to control the spot size of the electron beam. For a particular beam power (beam current x accelerating voltage) if high accelerating voltage is selected, beam power can be reduced.

This in turn reduces the number of electrons in the beam, due to less heating of the cathode and resulting less electron emission. With fewer electrons the beam gets narrower and spot size is reduced as determined by the relation -

$$\text{Spot dia} = \left(\frac{\text{Beam Current}}{\text{Accel.Voltage}} \right)^{3/8}$$

But the same influence on spot size can be achieved by the electronic optics system with focusing coil. Hence, in the recent EB machines accelerating voltage is given only a superficial importance. This voltage is normally limited to 30 KV - 150 KV.

3.2 Beam Current:

With constant accelerating voltage the depth of penetration attainable with a given machine depends, on the beam power which is directly proportional to the beam current. The beam current is regulated by controlling the potential of the control electrode (Wehnelt). The current range in modern machines varies from 50 milliamp to 1 Amp.

3.3 Beam Focus (Refer Fig.4b):

The weld quality in EBW, especially penetration to a large extent depends on the position of the focal point of the beam in relation to the workpiece. The beam diameter at the workpiece is dependent on the position of the focal point and thus the power density is varied. As a consequence, certain defects like porosity etc., can be eliminated by adjusting the beam focal points. Excessive control on the beam focus can also be harmful as a slight misalignment can cause lack of fusion in the root, though the beam may be seen perfectly aligned at the top of the workpiece. Accordingly, beam spot size at the workpiece is normally adjusted to be about 0.5 to 0.8 mm in diameter.

3.4 Welding Speed:

Like in any other arc welding, welding speed directly controls the heat input. Higher welding speed results in a decrease in the energy input per unit length of the weld and penetration is reduced. Too low a speed would result in heat losses through conditions and the weld width increases. The correct choice of the welding speed depends on the depth and width of the weld desired and also on the physical properties of the materials being welded (like Thermal conductivity, etc).

4.0 COMPONENT DESIGN - CAPABILITIES OF EBW

4.1 Very Low Heat Input:

The fusion zone in joints welded by EBW process is so narrow that the least possible material disturbance is produced. In deep penetration welds (in thicker plates), the heat input can be as little as 1/5 of that encountered in arc welding process.

Distortion of their welded component is the consequence of two distinct factors -

a) Thermal distortion resulting from the excessive and local heating; and

b) Displacement of the component parts due to shrinkage during solidification of the weldment.

Both these effects are very much less in EBW. For example, when welding a steel section, 12.7mm thick, a shrinkage allowance of only 0.1 mm is required for EBW. as against 0.5mm for arc welding (Fig.7).

This advantage indirectly reduced the cost of fixtures required during welding. Also the component parts can be finish machined before integrating by welding thus reducing the cost of machining.

The magnitudes of the internal stresses produced in the component is very much less in EBW due to the low heat input characteristic. This reduces the tendency of the weld to crack in service.

4.2 Welding Unweldable Materials:

Due to the cracks produced either during welding or after heat treatment certain materials are considered unweldable by conventional welding processes. These cracks are produced due to strain induced by shrinkage exceeding the fracture strength of the HAZ or the weldment. Since the shrinkage strains are small in EBW, certain materials which have this cracking tendency when welded by conventional processes may survive with EBW.

4.3 Long Focus Capability:

The focal length of an EB system is quite high. The gun to work distance can be as long as 1.2m. So, it is no longer necessary to place the heat source immediately above the component surface, as in electric arc, gas or plasma jet. Thus welding in narrow and restricted areas where keeping a torch or electrode is difficult can be easily done with an EB system (Fig.8).

The beam size being very small (0.6mm), reaching inaccessible areas with complex or fine geometries is not difficult task in EBW (Fig. 9).

4.4 Wide Range of Thickness:

By adjusting the welding parameters, welding can be done over a wide range of thickness (0.1-100mm). It is also possible to weld dissimilar thickness components. In conventional welding methods such a possibility is precluded since heat is transmitted to the metal by conduction. If the area heat is set for fusing the thin section it may not be adequate for the thicker one, but if it is set high the thinner one melts away. By contrast, with EBW the heat is generated within the material when the electron impings.

By off-setting the beam slightly towards the thicker section welding of dissimilar thickness is made possible.

4.5 Welding Dissimilar Metals:

Due to the precise heat control capability of EBW welding of dissimilar metal is very much simplified. This results in considerable cost saving in production.

4.6 Welding Speed:

Welding speeds by EBW are ten times faster than electric arc methods when penetration is done in a single pass in both cases. Single pass welding in thicker plates can be produced with increased beam power thus considerably reducing welding time. Also the repeatability of the EB welds are high compared to other processes.

5.0 JOINT DESIGN

EBW offers a greater freedom to the designer by virtue of its localised nature of the heat spot, long working distance, the ability of the beam to find its way to the joint through narrow gaps, and the possibility of welding in areas close to finish machined surfaces.

5.1 Butt Joint:

Butt joint is the generally recommended joint for fabrication of EBW. But it deserves special attention. In electron beam weld the weld zone narrows down from relatively wider upper bead to virtually a line joint at the lower bead (Fig.10). This excessively narrow zone results in root porosity (Fig. 11). This may be due to the metal vapour generated at the centre of the molten column which is unable to escape the narrow slot at the bottom of the joint interface. Upon condensation and solidification a void is formed.

In deep penetration welds it is difficult to achieve fusion of the whole depth if the fusion zone narrows down to a 'Dagger' edge (Fig. 12). Even a small variation in weld parameters produces variation in penetration along the weld seam which can be observed in the lower seam as a 'beady' appearance (Fig. 13). To get healthy lower bead weld parameter selected should be greater than that set for truly narrow weld, resulting in slight increase in heat input. Even with this the net heat input is much less than that of arc heat.

Excessively wide weld may result in deep through and channelling on the upper surface leading to stress concentration (Fig. 14). So good weld geometry should be chosen for butt welds.

A lip preparation (Fig. 15) used in butt welds provides the additional material for getting satisfactory upper and lower beads. A slight variation in the above geometry as shown in Fig. 16 helps in easy alignment of the two parts. But the weld line is blind and has to be marked on the top surface.

Integral or separate backing support to the lower bead helps in achieving a full penetration joint (Fig.17, 18). The backing can be removed after welding for inspection of the lower bead.

5.2 'T' Joint:

Such joints commonly occur in structural fabrication and can be welded by various techniques as mentioned below -

i) By nailing a weld through the horizontal member into the thickness of the vertical one (Fig.19). This may be acceptable for some applications. But it is a blind weld and root porosity is likely to occur. The lower bead cannot be inspected. The whole joint is held by a narrow section of the weld nugget;

ii) EB being small and can be focussed at any point accurately the same 'T' joint can be done by injecting the beam at an angle to the surface as shown in Fig.20. The weld must be wide enough to allow for an approach angle(Fig.20)

Still better arrangement is as shown in Fig.21 resulting in reduced stress concentration effect;

iii) The same 'T' joint can be achieved by means of two lap joint as in Fig.22;

iv) Another variation is to produce two butt joints as in Fig.23 to get the 'T' joint.

5.3 Flange to Shaft Joint:

Such joints are often found in hydraulic and mechanical drive application. Normally they are made by cutting a hole in the flange for matching the tube and joining them by a planetary butt weld (Fig.24). In this, the beam has to approach the pipe surface at a small angle. It may cause geometrical stress concentration. An improvement over this is to do butt welds by slight modification of the pipe geometry as in Fig.25.

But both these planetary welds are difficult to achieve due to the progressive shrinkage taking place as the weld proceeds making it difficult to close the gap at the end of the weld.

Even if the weld is achieved stress concentration will be there resulting in cracking during heat treatment. To avoid this it is better to employ a circumferential weld as in Fig.26. The diameter of the hole in the flange is equal to the inside diameter of the shaft. Easy and stress free joints can be produced in this case since the component parts are free to move in the direction of the shaft axis to accommodate shrinkage displacement. A local increase in flange thickness as in Fig.27. Improve the accessibility for welding and reduces the stress concentration in the weld zone.

5.4 Lap Joint:

A lap joint should be avoided whenever possible and replaced by a butt joint. But it is easier and cheaper to prepare and in certain applications may be acceptable. The simplest EBW lap joints are as in Fig.28. The load bearing area can be extended as in Fig.29. It is preferable to convert these joint into butt joint as in Fig.30.

5.5 Design for Inspection:

Whenever joint design is selected the main consideration should be the accessibility for inspecting the lower bead. The lack of penetration can be established only by a visual inspection.

6.0 EFFECT OF THE INTENSITY OF VACUUM IN EBW

6.1 Effect of Pressure on Beam Concentration:

Electron beam undergoes very little scattering from collisions with gas molecules in a high vacuum (about 10^{-4} torr). Concentration of gas molecules in the vacuum chamber is of very low level and hence the frequency of electrons getting collided with gas molecules is very less as shown in Table-1. Hence the beam can be held in a sharp focus over a greater gun to work distance still producing the characteristic deep, narrow welds. When the chamber pressure reaches around 10^{-3} torr scattering becomes significant resulting in wide bead with lower penetration. The gun to work distance has to be made shorter under such conditions. At atmospheric pressure (760 torr) even at 150mm beam scattering becomes so high as to make the weld impossible at greater distance.

6,2 Effect of Pressure on Weld and HAZ:

The contamination level in high vacuum (Table-1) is very less. The weld metal and the HAZ gets complete protection from oxidation and harmful gases. This is very essential while welding reactive metals like zirconium and titanium.

Also welds made in a high vacuum are narrower with narrow HAZ, than comparable welds in medium vacuum (10^{-1} to 10^{-2} torr) or at atmospheric pressure. The narrow width of the tempered zone in hardenable steels and other hardenable alloys permits welding of these metals without loss of strength.

7.0 COMPARISON OF VARIOUS CHAMBER VACUUM LEVELS - (REFER TABLE-2 AND FIG.31)

EBW is done at various vacuum levels depending on the specific application requirements. They are classified into -

i) High vacuum (10^{-5} torr)
ii) Medium vacuum (10^{1} to 10^{-3} torr)
iii) Non-vacuum or out of chamber welding

No doubt the high vacuum level gives a good weld with weld metal quality equvalent to that of vacuum degased materials. But the pumping time to achieve such high vacuum level is a major limitation in

TABLE - II

COMPARISON OF EB WELDED CHARACTERISTICS

CONDITION	High vacuum	Medium Vacuum	Out of Vacuum
Max. KV	30 - 150	60-150	150 - 175
Max. Power	30 KW	25 KW	12 - 25 KW
Max. working distance (Gun to work distance)	250 mm for 30 KV to 1000 mm for 150 KV	Less than 1000 mm for 150 KV	About 15 mm
Work chamber pressure	10^{-4} torr	10^{-2} - 10^{-3} torr	Atmosphere
Max. workpiece penetration (Stainless steel)	50 mm at 60 KV 125 mm at 25 KW	50 mm at 75 KW 100 mm at 25 KW	15 mm at 12 KW 22 mm at 25 KW
Pump down time	1 min to 20 min. (Depends on chamber size)	1 - 20 sec. Based on chamber size)	None
Versatility	Limited for high volume production good for reactive materials.	Good for high volume productions limited for reactive materials.	Poor But better than TIG or arc welding especially in inert atmosphere.

welding large components. Diffusion pumps are used to get such high vacuum. The effect of this limitation on unit production time is reduced by welding a number of assemblies in each load and by keeping chamber size as small as possible. Special chambers having opening and scale that permit oversized work to extend outside the chamber or by the use of a portable clamp on chamber, circumvents the difficulty of welding large components. The chief advantage of medium vacuum is the short pump down time and hence it permits mass production of parts. A mechanical pump is sufficient to achieve this vacuum level. Even with medium vacuum contamination level is much less than those actually observed for inert gas shielded arc welding. Penetration is 5 to 10 times less than for high vacuum weldings are wider and slightly more tappered. Beam deflection and oscillation can be used in medium vacuum. Normal applications of medium vacuum conditions are welding of automobile parts such as gears, shafts, etc. In medium vacuum welding also the gun is kept at a high vacuum level.

Production rates are made still higher by welding in 'out of chamber' condition still maintaining the gun alone at high vacuum level. But this advantage is gained at the expense of reduced penetration and working distance. To provide an electron beam of sufficient velocity to offset the scattering effect of collisions with gas molecules. The accelerating voltage is kept high (100-175 KV). The gun to work distance is often between 6 and 18mm. The beam energy is controlled by altering the beam current and welding speed.

The small size of the exit orifice on the electron gun makes it necessary to focus he beam at or very close to the exit orifice. Hence, it is not possible to vary weld characteristic to a significant degree by changing focus. Beam deflection and oscillation are not possible in non-vaccuum condition. But the beam width is great enough to prevent undercut or porosity at the root of the weld.

A cosmetic pass is needed to get a smooth crown to ease the inspection of the as welded surface in welds made at atmospheric pressure. A stream of dry filtered air, or an inert gas is passed across the weld region to minimise entrance of welding vapors and other contaminants into the gun. The weld penetration in non-vacuum seldom exceeds 12mm without substantially reducing the welding speed. The weld penetration in atmospheric condition depends on welding speed, material and the gun to work distance (Fig.32) with a shielding gas, penetration depends on the molecular weight of the gas. The relative capacities of these gas molecules to scatter the electrons decides the penetration. Thus Helium gas having less molecular weight than air and argon gives a deeper penetration than others. The penetration ratio is about 2:1:0.5 respectively of helium air and argon gases.

Non-vacuum welds are wider and more tapered than high or medium vacuum welds. Compared to high vacuum welds heat input in non-vacuum condition is nearly 40% higher to achieve same penetration level.

But this heat input (in non-vacuum) is only 32% of that required for TIG for the same penetration level. Also the maximum weld width is only about 56% compared to TIG. Hence weld shrinkage across non-vacuum EBW is less (50%) than that of TIG welds on the same work metal and thickness.

Non-vacuum EB welding is used for commercial production of gears, wheels, ball joint, components for refrigeration and other applications.

TABLE-1

Pressure	No.of Molucules	Relative frequency of collisions
10^{-5}	5,800	1
10^{-3}	5,80,000	100
10^{-1}	58,000,000	10,000
769	$\simeq 4.4 \times 10^{20}$	100,000,000

Effect of vacuum on Electron scattering due to collisions

8.0 METALLURGICAL CONSIDERATIONS OF EBW

Electron Beam Welding approaches towards the ideal fusion welding process as it results in the minimum thermal disturbance in the work piece for a given depth of weld. Still the same basic difficulties as any other fusion welding processes including cracking, porosity,hardening and softening exists in EBW.

The thermal strain and metallurgical effects are inter-related. The reduced thermal strains and metallurgical effects have enabled a great many unweldable materials to be satisfactorily jointed by EBW including several dissimilar metal combinations.

The extent of heat spread into the workpiece controls the extent of the associated strain field. Narrower the strain field the less chance there is of cracking. Narrow welds (characteristic of EBW) will produce high rates of induced strain which might increase cracking tendencies. But the narrow strain field reduces the risk of cracking. Whichever effect is predominant depends on the material and its strain rate sensitivity.

Higher welding speed attainable using EBW helps in achieving a weld with grain boundary condition almost free from liquiation in the HAZ. This is due to the rapid thermal cycle reducing the occurrence of liquiation and thus cracking can be avoided immediately after welding or on post weld heat treatment.

When welding refractory alloys of high melting point, grain growth is inevitable if conventional arc welding process is employed due to lower welding speed. EB reduces both the width of the HAZ and the extent of grain growth substantially giving rise to marked improvement in tensile strength and ductility. The fusion zone in an EB weld is effectively a fine grained cast structure. Often with directional solidification towards the centre line of the weld. The cooling rate of the weld in EB is higher than with-in the weld. In the parent metal, thermal effects, which may result in hardening or softening are confined to narrow band.

Softening can occur either through loss of a work hardened structure or solution treatment or over ageing in a precipitation hardening material.

When welding precipitation hardened material with conventional processes, the weld metal and some portion of HAZ are softened by dissolution of the precipitate phase at the high temperature to which these regions have been subjected. Further away from the weld metal, there is a zone which is overaged due to the existence of the appropriate ageing temperature for a relatively long period in this region.

To regain the original hardness of the material full heat treatment cycle involving the whole component is required which may cause distortion of the structure with EBW, the solution treated areas are narrow and the overaged region is almost undetectable in some materials and the joint properties are not affected much. A low temperature ageing treatment is sufficient to recover the original strength after welding. This property of EBW is very useful for welding of aluminium alloys.

Due to the high depth to width ratio, joint property of EBW is mainly determined by the parent metal, in the case of materials containing dissolved gases. Non-ferrous metals such as aluminium and titanium alloys arc welded at above 50 mm/sec welding speed to suppress gas evalution and steels at lower speed to allow adequate time for vacuum degassing of the weld pool.

Use of high frequency beam or oscillation at 500 HZ helps in eliminating porosity permitting steels with high gas content such as semi-killed steels to be welded satisfactorily.

A 'Blind' weld (weld which does not penetrate the full thickness of the material) like that by welding through the horizontal member with partial penetration through the vertical component results in porosity at the root. This occurs due to entrapment of the penetration vapour cavity.

9.0 DEFECTS AND CONTROL METHODS IN EBW

9.1 Porosity:

This occurs due to evolution of trapped gas from liquid metal. The gas can be present in the material to be welded either in solution like H_2 in aluminimum or as free gas pockets may evolve due to a chemical reaction during welding like $FeO + C \rightarrow Fe + CO$. Porosity may also arise from surface contamination by grease or oxide containing moisture. By proper preweld treatment like degreasing, pickling or wire brushing surface contaminations should be removed. Material like Magnesium and Aluminium alloys contain surface oxides. If welded in the as received conditions they cause porosity. Cleaning solutions based on cromic oxide successfully cleans the oxides.

The welding conditions should be selected such as to reduce the porosity. A blind weld should be avoided wherever possible since root porosity causes stress concentration and the joint may fail under fatique loading. Wide weld should be used to minimise occurrence of root porosity since this gives the best chance of metal flow into the cavity.

9.2 Hardening:

Due to the faster cooling rate of EBW hardness in the weld zone is high. With steels which are hardenable by phase changing or cooling,martensitic structure may occur if the cooling is faster as in EBW. The hardness reached depends on the carbon content also. If the hardness is very high,welds will be prone to quench cracking under conditions of high restraint. For small components, a post-weld heat treatment can be done with the low focused beam to avoid such cracks.

9.3 Cracking:

The chance of cracking with EBW is reduced in comparison with conventional fusion welding processes although cracking still presents a problem for many materials and joint designs.

9.3.1 Solidification cracking:

This occurs due to the presence of the low melting point compounds formed by impurities like sulphur and phosphorus in steel. This crack occurs during the final stage of solidification due to large strains in the grain boundaries developed by the presence of the low melting point compounds at temperature where the bulk of the material is solid.

This cracking can be reduced by in EBW by the use of transverse beam oscillation.

9.3.2 Necklace cracking:

This is a form of defect which is peculiar to EBW and has been found in a variety of materials including titanium alloys, stainless steeis, nickel alloys and carbon steels. It occurs mainly in blind or very narrow fully penetrating welds. It occurs due to the inability of the molten metal to reach the penetration cavity and wet the side walls. An alternate explanation for this defect is that the stresses associated with the large temperature gradients and cooling rates at the root of a narrow weld are sufficiently high to initiate rupture which propagates as crack under service. This type of defect can be eliminated by widening the weld. This improves the ability of the metal to flow into the cavity and reducing temperature gradients and cooling rates.

10.0 TYPICAL APPLICATIONS OF ELECTRON BEAM WELDING

10.1 Welding of Nuclear components:

Electron Beam Welding finds extensive application for the fabrication of nuclear heat exchangers and other initial components. The basic reasons for employing this process can be classified under three categories (a) difficult to approach joints, (b) high degree of dimensionless flatness/ tolerance required, not attainable using conventional welding techniques and (c) rigid quality control requirements.

The calendria (Plenum) forms the heart of a nuclear reactor and this is the largest nuclear component involving about 700 joints on which EB welding process has been successfully used. The end requirements of stringent flatness tolerances, besides other practical considerations including time and cost rules out the use of other conventional welding techniques. Usage of Electron Beam Welding has been reported to produce defect level as low as 0.7% . The machine employed for such fabrication is of capacity 45 KW with partial vacuum chamber.

Another nuclear component reported to have been successfully fabricated using EB welding process is the reactor coolant channel components. This job involves welding of about 600 tubes of various diameters, lengths and thicknesses. The straightness tolerance is 0.15 mm over any meter length. Usage of GTAW process resulted in frequent weld repairs and many post weld operations. The job was welded using a EB machine having 45 KW capacity at a welding speed of 63 cm/minute.

The third component viz. a cover and sleeve assembly was also welded using Electron Beam process. In this application, the welding joint is situated 27 mm below the top surface and the entrance bore is only 25 mm diameter. Usage of conventional TIG welding process posed problem of designing a special torch and incomplete penetration. The job was completed employing EB process using beam rotation using circle generating device of the EB machine.

10.2 Welding of instrumentation capsules:

In the design of instruments for measuring pressure or load, sensing devices are used whose movements enable a mechanical or electrical signal to be generated for the purpose of display or control. The sensing device is normally a single diaphram or a combination of diphrams welded together to form capsules, or one piece hydraulically formed bellows. The alloys most frequently used in the manufacture of capsules are beryllium/copper, nickel/copper, nickel/chromium/iron, nickel/iron alloy or stainless steels of various types. The individual diaphragms are invariably thin 0.125 mm being most common. In a welded capsule assembly, these flexible components may distort during welding of the heat input is high, resulting in unsatisfactory performance. The joint integrity has to be high because of the high stresses, which may be encountered in operation. These stresses are of a cylic nature, thus fatigue stressing the joint. When the instrument is used for sensing pressure, leakage testing is applied to the weld, often to mass spectrometer standards.

Argon-arc welding has been used successfully for a number of years, but it has been found that EBW not only produces joints with improved strength and leak characteristics, but also confers additional design flexibility. Two stainless steel diaphrams 0.15 mm thick have been welded back-to-back at a diameter of 12.7 mm by inserting a washer of the same material and thickness as the diaphrams between them. All three items were welded together by positioning the beam through the gap and using the washer as a filler. This has been achieved by keeping the diaphrams spaced 1.6 mm apart at the periphery. Such an operation is not possible by conventional techniques.

BASIC LASER THEORY

1.0 THE LASING PROCESS

The term "laser" tells us that a simplified thumbnail description of the lasing process could be "opposite of absorption". At the heart of the lasing phenomenon is the ability of photons to stimulate the emission of other photons, each having the same wavelength and direction of travel as the original. According to quantum theory, atoms and molecules have discrete energy levels, and can change from one level to another in discontinuous jumps. The energy change required for a jump is provided by the atom's absorption or emission of a burst of electromagnetic radiation. The radiation frequencies involved and the energy spacings between levels are characteristic of the atom, and thus differ from element to element. The wavelength of each photon is related to its energy E by $\lambda = ch/E$, where h is Planck's Constant, and C is the speed of light.

Under normal conditions, most atoms or molecules remain quiescent at their lowest energy level, or ground state. But if these particles are excited into higher energy states--by an intense flash of light, an electrical charge, or other means--they will, in dropping back to the normal ground state, emit incoherent light in the process. (This is what happens in fluorescent lamps and some types of street lights). In a laser cavity, such emitted photons are trapped between highly polished and parallel mirrors, forcing them to bind back and forth in the cavity. Whenever a photon passes close to another excited particle of the same wavelength, the second particle will also be stimulated to emit a photon that is identical in wavelength, phase, and spatial coherence to the first. Both photons are now capable of stimulating the emission of more photons like themselves, and these, too, become part of the growing wave between mirrors (Figure 33). Lasing begins when enough photons are present, and if one of the mirrors is partially transparent, a highly disciplined, intense, and now-coherent beam is emitted.

2.0 FUNDAMENTAL REQUIREMENTS FOR LASING

All lasers include three fundamental elements; a lasing medium--one which provides atoms, ions, or molecules that support light amplification; an energy source to excite the medium; and an optical resonator to provide feedback of the amplified light. Figure 34 illustrates in schematic form the basic elements used in a carbon dioxide (CO2) laser.

Not all materials can qualify as lasing media, since the successful lasing medium must be excitable enough to achieve a condition known as "population inversion". This condition is essential in producing a net gain in the light being generated. That is, more photons must be generated by the medium than are being absorbed.

A number of materials, including solids, liquids, and gases, will support light amplification in this manner. But because the major emphasis in this text is on the use of CO_2 lasers, further discussion of population inversion will be based on the behaviour of the CO_2 molecule.

3.0 The CO_2 Population Inversion

There are several electron energy states above the ground state which the CO_2 molecule can temporarily occupy. When a CO_2 molecule decays from the higher energy level, it drops to an intermediate level. Energy released by the transition has a wavelength of either 10.6 or 9.6 micrometers, depending on the energy level difference between the higher energy level and the intermediate level. The transition producing 10.6 micrometer wavelength is more efficient for CO_2 molecules; for this reason, the CO_2 beam is utilised at, and characterised by, this wavelength. High voltage electrical discharges are used to excite CO_2 molecules to their higher energy states. In a pure CO_2 environment, each level receives a share of the molecules but the lower energy states gain the most, preventing the formation of a population inversion.

To make a population inversion possible, the CO_2 medium must be modified in some way. This is done by mixing Nitrogen (N_2) gas molecules with the carbon dioxide. Helium (He) is also included in the mixture, but its purpose is to increase thermal conductivity. One of the high energy states of N_2 molecules is very close on the spectrum to the high energy state of CO_2 molecules. As a result, some N_2 molecules are able to supplement the CO_2 population at this high energy level through resonant transfer of energy. And since no coinciding energy levels occur between the two gases at lower energy states, the population at high energy level is increased over lower levels, achieving the necessary population inversion.

Once the population inversion is established, the supply of photons continues to build until a state of equilibrium is reached. This state is brought about by an increasing decay rate at the upper level, although the number of photons is increasing. The effect is to reduce the population at the higher level and increase it at the lower level. Equilibrium occurs when the number of upper-level molecules exceeds the number of lower-level ones by just enough to make up for other energy losses. Chief among the losses, of course, is the emitted laser beam.

4.0 THE LASING SEQUENCE

The resonator (illustrated in Fig. 34)determines all of the laser beam characteristics except wavelength. In CO_2 lasers the resonator consists of a heat-resistant glass tube, with a precisely aligned mirror at each end. One of these mirrors is 100 percent reflective at 10.6 micrometers, while the other reflects some prescribed portion of the light, such as 85 percent. The light wave builds up in the resonator as it makes several hundred round trips between the opposing mirrors (all of this taking place within a few microseconds). On each round trip, a fraction of the radiant energy (15 percent in the example above) is transmitted through the partially transparent mirror, forming the laser's output beam. If the laser is in the pulsed mode, emission is in short bursts; if it is in the CW (Continuous Wave) mode, the light is continuous.

In the resonator the gas molecules are in the ground state because no excitation energy is present. When excitation voltage is first applied to the medium, many molecules are excited to a higher energy state and photons are emitted spontaneously. If an emitted photon collides with an excited molecule, amplification occurs, as that molecule will be stimulated to produce a photon identical to the first one and travelling in the same direction. Stimulated emission proceeds, as each of the photons is now capable of causing the production more. Photon motion can be in any direction, but those which happen to travel parallel to the tube axis will strike an end mirror and be reflected back.

It is these photons which build up the coherent, single frequency light wave in the tube as they bound back and forth between mirrors, stimulating the emission of more and more identical photons in a chain reaction. Some of these photons pass through the partially transmissive mirror (the output coupler) and emerge as a beam of parallel rays, while others continue to oscillate in the resonator, generating more photons. This phenomenon will continue among the lasing medium molecules.

5.0 PROPERTIES OF LIGHT

Incoherent Light Vs. Coherent Light -

The properties of light produced by lasers may be more easily understood if we draw a contrast between their light and that from an incandescent source.

As shown at the left in Fig. 35, an incandescent source emits photons randomly in time and space. That is, its radiant energy is undisciplined and said to be "incoherent". It is also known as "White light" (containing all colours of the visible spectrum). If the power density of a 100 Watt incandescent source is measured at a distance of 1 metre, only 0.8 milliwatt per square centimeter is detected. It is impossible to focus all of this source's radiant energy into a spatially coherent, collimated beam.

But note, at the right in Fig. 35, how a laser emits light in a spatially coherent beam. This beam is almost perfectly collimated (has parallel rays), with a typical axial divergence of only 1 to 2 milliradians (in a TEMOO beam from a CO_2 laser). A beam with this low divergence can have an intensity - also called "power density" of several hundred watts per square centimeter, 1 metre from the laser source. It is also monochromatic as it occupies a very narrow band on the spectrum. Helium-neon lasers, for instance, glow with the brilliant red light of their wave length in the visible spectrum. CO_2 lasers, however, have invisible light because they emit in the far infrared spectral region.

A laser beam can be focussed by a lens to a small spot, the size of which is theoretically limited only by beam divergence and diameter, light wavelength, and lens focal length. For example, the beam of light from a 100 Watt CO_2 laser can be focussed down to a spot 0.005 inch in diameter.

6.0 TYPES OF LASERS

Although the birth of laser technology can be dated as recent as 1959, many kinds of lasers are now commercially available. Some of the most important industrial lasers are listed below -

GAS	SOLID STATE
Argon	Synthetic Ruby
Carbon dioxide	Gallium-Aluminium-Arsenide
Helium-Cadmium	Gallium-Arsenide
Helium-Neon	Nd:Glass (Neodymium:Glass)
Krypton	Nd:Yag (Neodymium:Yttrium-Aluminium-Garnet)

There are many types other than those listed here that are of scientific, medical, and military importance, or used in communications and other fields.

Industrial lasers in which a gas is used as active medium are far more abundant than those with other lasing media. While many gas lasers employ a homogeneous lasing medium, some of them rely on a mixture of gases to obtain a more efficient transfer of energy into the lasing level, as noted with the CO_2 laser. In such a mixture, the key lasing material need not be the largest in volumetric proportion.

Of the gas lasers, the CO_2 is the type most commonly used in industrial applications. Its utility derives from the high power that can be generated at a wavelength suitable for processing a great variety of materials. An electric discharge is the most common source for exciting the lasing medium (known in industry parlance as "pumping" the laser).

Solid-state lasers are represented by the least variety of lasing media, although a synthetic ruby rod was the first material to achieve the lasing phenomenon. Of the solid state lasers, Nd: YAG and Nd: Glass types are the most commonly employed in industrial applications. Both are pumped by intense light from flash lamps.

Contemporary lasers exhibit a broad range of light energy and power output characteristics, briefly summarised in Fig. 36. The wavelength of light obtained extends from 325 nanometers for the He-Cd laser to 10.6 micrometers for the CO_2 laser.

Operating Characteristics:

Lasers may be operated in either the continuous wave (CW) or pulsed mode, with some systems employing pulse repetition rates upto 50,000 per second. In a few, pulses of only 10 picoseconds duration can be achieved.

The output range is also extremely wide. Many lasers commonly used in industry, such as the familiar red helium-neon types used in alignment, printing, measuring, and display, are rated in milliwatts. Yet upto 100,000 watts of single-beam power can be produced by a continuously operated CO_2

..10/-

TYPE	WAVE-LENGTH (nm)	OPERATING MODE	MAX.REP RATE (pps)	PULSE WIDTH	POWER TEM00 (watts)	MULTIMODE
He Ne	632.8	CW	-	-	0,0005 0.015	
Ar	451.9 to 514.5 488.0 or 514.5	CW	-	-	20 10	-
CO_2	10.6(m)	CW	-	-	500	Up to 100,000 WATTS
	10.6(m)	PULSED	2,500	100 sec LONGER	-	4,000 for 500 CW
CO_2 TEA	10.6	PULSED	400	400 Sec	-	100,000
He Cd	325.0	CW	-	-	-	-
KRYPTON	350.7 to 799.3	CW	-	-	6	-
NITROGEN	337.1	PULSED	to 500	10 sec	-	250,000 (2.5mj)
Nd: GLASS	1.06(m)	PULSED	1	(500 sec (10 msec	-	10^6 (125j)
Nd:YAG	1.064(m)	CW	-	-	20	200
	1.064	PULSED (FLASH-LAMP)	400	(100 sec (12 msec	-	400(20j)
	1.064	PULSED (A.O.Q-SWITCH)	50,000	200 sec	-	50(5mj)

Axial-Flow CO_2 Laser:

This is the most simply constructed and efficient of the gas lasers and is the type most often used in industrial applications. As illustrated in Fig.37, it consists of a glass tube which contains the gaseous lasing medium. An axial flow of gas is maintained through the tube to replenish those molecules depleted by the effects of the multikilovolt discharge of electricity used for excitation.

A mirror is located at each end of the discharge tube (laser tube) to complete the optical resonator cavity. Typically, one mirror is totally reflective at the wave length of light produced in the cavity and the other mirror is both partially reflective and partially transmissive. The latter, referred to as the output coupler, allows a proportion of the light to escape as the laser's output beam.

An axial-flow laser is capable of generating a beam of coherent light having a continuous-power rating in excess of 50 watts for every meter of resonator length. To achieve stable TEM modes and power levels, it is necessary that the mechanical structure of the resonator be extremely stable. Various configurations of the resonator cavity can be used to obtain long optical path lengths without increasing the overall length of the laser. As shown in Fig.37, combinations of precisely aligned mirrors are used to bend the internal laser beam.

Transverse Excited Atmospheric Laser:

The transverse excited atmospheric CO_2 laser (TEA) is capable of producing pulsed output beams of very high peak power, and thus is useful in certain industrial applications. The gaseous lasing medium is maintained at atmospheric pressure and is excited by an electric discharge from electrodes placed longitudinally along the optical cavity (resonator), as illustrated in Fig. 38.

Because the electrodes in the TEA laser arc parallel to the major axis of the resonator, a relatively low potential is required to maintain.

Very short discharge times make possible the electrical discharge in the gas at high pressures of one atmosphere or more. At these pressures, the density of the CO_2 molecules is much higher than in the conventional long discharge tube. TEA lasers can, therefore, generate 10 megawatts or more of power in a single pulse of light less than 1 microsecond long. These lasers are usually operated at low repetition rates of a few pulses per minute.

The TEA laser beam is extremely uniform with respect to its wavefront, making this type of laser useful in noncontact package labeling. In that application, a mask is placed in the beam at a location distant from the item to be marked. The pattern of the mask is then reimaged on the package surface. TEA lasers are also employed in some materials applications, such as drilling, but their main use at present is in research laboratories.

Gas Transport Laser:

The gas transport laser (GTL) operates by combining the principles of several other types of gas lasers. Its main advantage is that it can generate a large amount of beam power within a relatively small resonator structure. As illustrated in Fig. 39, the gaseous lasing medium is continuously circulated across the resonator cavity by a highspeed blower. Thermal stability in the medium is maintained by a heat exchanger. Recombination of gas molecules after excitation, is enhanced by the action of chemical catalysts.

Excitation in the GTL is accomplished by a discharge between electrodes positioned parallel to the optical axis. Because the volume of the resonator is large relative to its length, large mirrors can be placed at each end to reflect the beam through the discharge region several times before it escapes through the output coupler.

The ability to achieve a long effective optical path in a short actual distance allows the gas transport laser to be a compact structure that generates high output power. Continuous wave lasers capable of output power between 1 and 5 kilowatts are commercially available.

Solid-State Laser:

For an active medium, the solid-state laser uses lasing ions which are suspended in a rod-shaped solid matrix. These "dopants" in the rod are excited by a source of intense light. This may be either one or two cylindrical flashlamps, as shown in Fig. 40 or a helical flashlamp which surrounds the rod. If two cylindrical flashlamps are used, the laser rod is placed between them at the common focus of two ellipses whose other foci determine the placement of the flashlamps (see bottom of Fig.40). The distance between foci, in each of the two ellipses sharing a common focus, is defined by the configuration of an elliptical reflector that surrounds the excitation sources and the laser rod. This arrangement provides an efficient coupling of excitation light into the lasing medium. A water cooling system controls the temperature of the rod and flashlamps.

Three major representatives of this type of laser are made of synthetic ruby of neodymium: glass.

(Nd: YAG). In each of these materials the lasing ions exist as minority dopants in the host matrix. For all three, flashlamp life is somewhat limited, and operating costs are higher than for CO_2 lasers, but certain advantages remain.

Solid-state lasers can be operated in several ways. One way is the excitation of the lasing medium (rod) with a capacitative discharge through the flashlamps(s), which results in the emission of a brief flash of light. This in turn excites the lasing medium into emitting a burst of light. For Nd:YAG this occurs at a wavelength of 1.064 micrometers. Using this excitation scheme allows pulses that last between 0.2 and 12.0 milliseconds, at repetition rates upto 100 pulses per second. At slower rates, the TEM multimode energy in each output pulse may be 20 joules or more for a typical commercially available laser; while at the most rapid rates, this will fall to approximately 2 joules per pulse (see Fig. 41).

Even at the highest repetition rates, the energy in each pulse is sufficient for drilling and spot welding metals. Since the wavelength of light emitted by a Nd: YAG laser is relatively short, the output beam can be focussed to a spot of small diameter.

Flashlamp-pumped lasers are capable of drilling holes as small as 0.001 inch in diameter but they are not wellsuited for drilling large holes because of the nonuniform distribution of energy across the output beam.

Switching: An Nd: YAG laser, like a CO_2 laser, may also be operated in a continuously pumped, Q-switched mode. Q-switching produces the effect of a shutter moving rapidly in and out of the beam, "spoiling" light production until very high energy storage is reached in the resonator. When the shutter opens (Q-switching is stopped), a large pulse of power is released.

The average output beam power available in this mode at various rates of pulse repetition (calculated as CW power) is represented as a dashed line in Fig. 42. The solid line in the figure shows the peak power per pulse that can be produced. Values shown in the graph are derived from a laser that was acousto-optically (AO) modulated within the optical cavity to generate the Q-switched pulses.

Such pulses are of very short duration, typically lasting 200 nano-seconds. In this mode, repetition rates of more than 25,000 pulses per second can be obtained, although at these high rates the energy per pulse is low if compared with the output of low-repetition rate CO_2 and flashlamp pulsed Nd:YAG lasers.

Q-switched Nd:YAG lasers are usually employed where material removal at low power levels is required, such as in the vaporization of thin films from surfaces. The sensitive removal of carbon from integrated circuit mounted resistors to adjust their resistivity precisely is a major application.

8.0 APPLICATION OF LASER

The high energy that is obtainable in the focused output of a laser beam enables the laser to be used as a source of thermal energy for such fabrication processes as melting, welding drilling, thermal practice and surface treatment.

Of the lasers available at present only CO_2, neodymium, ruby and argon ion lasers have sufficient power output to do more than evaporate thin films and upto now the high cost of argon ion lasers has precluded their use for fabrication processes. Neodymium and ruby lasers have been primarily used for applications requiring a pulsed output such as drilling, microwelding, scribing, and trimming. CO_2 lasers have been used for pulsed and continuous applications including scribing, cutting and welding. Although a high-power CW output is obtainable from neodymium lasers, the limited lamp life at high powers, poor stability, low efficiency and high capital cost have upto now limited its application. Of the power incident at the surface some will be reflected, some absorbed and some transmitted so that -

$$W_i = W_r + W_a + W_t$$

where the subscripts refer to the incident, reflected, absorbed and transmitted power respectively.

The effect of the absorbed power in the material is governed by the thermal properties of the material (thermal conductivity, diffusivity, melting point, vaporisation temperature, specific and latent heats) together with the density and geometry (which affects the thermal diffusion and conduction in the material). The heat transfer due to pulsed Q-switched and steady state lasers have been studied. In most fabrication processes, the heat input per unit volume is most important. For material removal where vaporisation takes place, the heat of vaporisation governs the process, but for welding the heat of fusion is important. The difference between the heat capacity at vaporisation and the capacity at the boiling point of the material is an important criterion for welding processes, a large difference implying a greater tolerance to power variation.

In drilling and some welding processes, the maximum power that can be used is limited by explosive ejection of material and formation of vapour above the material. At very high powers formation of plasma may also occur. Vapour and plasma formation tends to deform the laser beam and reduce its effectiveness.

Drilling:

The energy supplied for drilling should be such that rapid evaporation of material takes place before significant radial diffusion of heat into the workpiece o-curs, so limiting melting and the heat affected zone to the region adjacent to the hole. The maximum power density and the pulse length are limited by excessive vaporisation above the hole and at high powers the formation of a plasma plume which results in absorption of the laser energy in the vapour rather than the material.

Holes with high aspect ratios I/D where I is the thickness of the work and D is the hole dia) as high as 20:1 can be obtained due to the aperturing effect of the hole at the focus and multiple reflection from the side walls of the hole.

Maximum thickness of materials that can be drilled is about 2.5mm with hole diameter ratios of upto 20:1 using several pulses. Pulsed ruby and neodymium lasers are being used for drilling holes of small aspect ratio in hard metals which are difficult to drill by other methods. Application includes cooling holes in turbine blades.

Pulsed lasers have also been used to balance small rotating parts by metal removal. Watch balance wheels 0.1mm thick have been balanced dynamically with a split beam from a pulsed Nd:YAG laser by drilling holes 0.1 - 0.7 mm dia simultaneously from opposite side of the wheel. A pulsed neodymium and glass laser with an output of 2J is used for trimming mercury-in-glass thermometers by vaporisation of the column at a preset position causing the column to separate. Another established application is the use of ruby and neodymium lasers for roughing out and resizing diamond dies used for wire drawing. Final polishing is carried out by conventional abrasion techniques. Power levels of upto 1.5J per pulse at upto 10 pulses per second of about 200 $/^{us}$ duration are used. Hole sizes less than 0.025 mm can be obtained. Multiple pulsing combined with rotation of the diamond resulting in satisfactory hole symmetry. By off-setting the axis of rotation of the diamond from the axis of the laser beam large diameter holes can be bored. Considerable saving in time and reduction in use of the diamond grinding paste previously necessary are obtained. Watch jewels can also be drilled in this way and the process is in use in production applications. Similar Techniques are employed to remove flaws due to black spot impurities in diamonds.

The cutting process:

The cutting process is essentially one of material removal from the cut or kerf except in the case of thermal fracture. For cutting, a CW or pulsed output with a repetition frequency such that a series of overlapping holes results, is required to produce a continuous cut. The kerf width should normally be as small as possible without rewelding of the material taking place. This applies principally to plastics and can be taken as less than 0.025mm.

The effectiveness of a laser for cutting can be increased by the use of a gas jet coaxial with the laser beam and has been estensively used with CO_2 lasers. The depth of cut increases as the pressure is increased until a value of pressure is reached (about 2-3 bar) when further increase in pressure has no further effect. The cutting rate was largely independent of the gas used and gas pressure where the material does not react exothermically with the cutting gas. Cooling of the top surface of the material also occurs, resulting in a square cut edge. Even materials that burn in air, such as paper, can be cut, since the cooling effect outside the focus is normally large enough to prevent burning outside this region. Deep parallel sided cuts of high aspect ratios depending on the properties of the material can be obtained in excess of the depth of focus.

Most wood products can be effectively cut by a CO_2 laser with gas jet assistance and parallel cuts up to 50mm deep have been obtained and cutting rates of 50mm x 100mm section would at 19.8mm/min have been reported. Hard wood cut at slower speeds due to their greater density and higher thermal conductivity. The maximum cutting rate decreases as the density and the moisture content increase, but is virtually independent of grain direction.

One of the first viable industrial applications of CO_2 lasers has been for cutting precision slots in plywood used for steel rule dies for pressing out cartons in the packaging industry. More recent applications include cutting the wooden dies used for cutting out fabric linings for cars and gaskets both of which are in use in the automobile industry in America. The slots in the dies are used to hold the knives for cutting and inserting crease lines during the manufacture of cartons. Important requirements are a high accuracy and constant cut width together with a high degree of parallelism of the cut since the knives are held only by friction. An automated process of high accuracy is made possible by the non-contact cutting process which is not affected by non-uniformities in the plywood.

Brittle materials such as ceramics and glasses can be cut by scribing followed by mechanical fracture. Only a small amount of material is removed from the top surface of the material during the scribing process. A gas jet is not required and a pulsed output can be used. Fracture is obtained by flexing the material mechanically after scribing. Considerably lower power densities than those for cutting are needed and the heat affected zone is small.

A potential application is for cutting sheet metal below about 6mm thickness such as mild steel, stainless steel, nickel alloys and titanium. The main area of application is in the aircraft and automobile industries. The use of laser cutting is particularly attractive for cutting airframe and sheet metal used for engine exhaust podding when the limited number of components required precludes the use of dies and many of the materials used are difficult to cut by conventional methods. A related area of application is for cutting and trimming three-dimensional pressings used for jet exhaust systems and for cutting our damaged areas of engine chambers. Many of these applications are already in the course of development or in limited application in the aircraft industries.

Welding:

There are two principal types of weld, conduction limited and deep penetration. The depth-to-width ratio of the weld zone is about 3:1 for conduction limited welds and 10:1 or more for deep penetration welds. Pulse and CW lasers have been used for conduction limited welding in which the depth of the welded zone is limited by thermal conduction from the top surface. Conduction limited welds are characterised by the heat affected zone (HAZ) either side of the weld which is large compared with the actual weld depth.

A high degree of stability of the laser output is necessary for repeatable weld quality to be achieved. The absorption of most metals increases with temperature and is higher in the molten and vapour phases than the solid phase. As a result an unstable state is easily reached. The effect of varying geometry on the heat dissipation also affects the welding conditions. Variation in the laser output power and mode structure, particularly of pulsed lasers, due to internal heating and fluctuations in the output of discharge tubes used to excite solid-state lasers all result in variation in the welding conditions.

Some measure of the ease of weldability of metals is obtained from the ratio of the energy required to completely melt the material from the solid phase at the melting point over the energy required to reach the melting point.

Neodymium lasers are normally preferred to ruby lasers as the longer pulse length obtainable enables greater overall heat transfer to take place without excessive vaporization.

Lasers offer various advantages for continuous welding processes comparable with those obtainable by electron beam processes. A good bead finish is achieved because of lack of disturbing effects on the weld normally obtained with arc processes. Good fatigue properties are obtained because of the lack of undercut which occurs with electron beam processes. (This is probably due to the ability to use a shielding gas which permits enough oxidation to give a low surface tension at the bottom face of the weld). The heating mechanism is simpler and more controllable than arc or electron beam welding processes. Since wavelength of the radiation is of one value only, feedbabk of weld condition may be much easier because of the ease with which the impinging radiation may be filtered out and prevented from interfering with the sensor, enabling adaptation to automated welding processes. It is less demanding in the matter of access to the weld region than is an arc welding torch. As a vacuum chamber is not required it is readily adaptable to continuous throughputs and large structures.

* * * * *

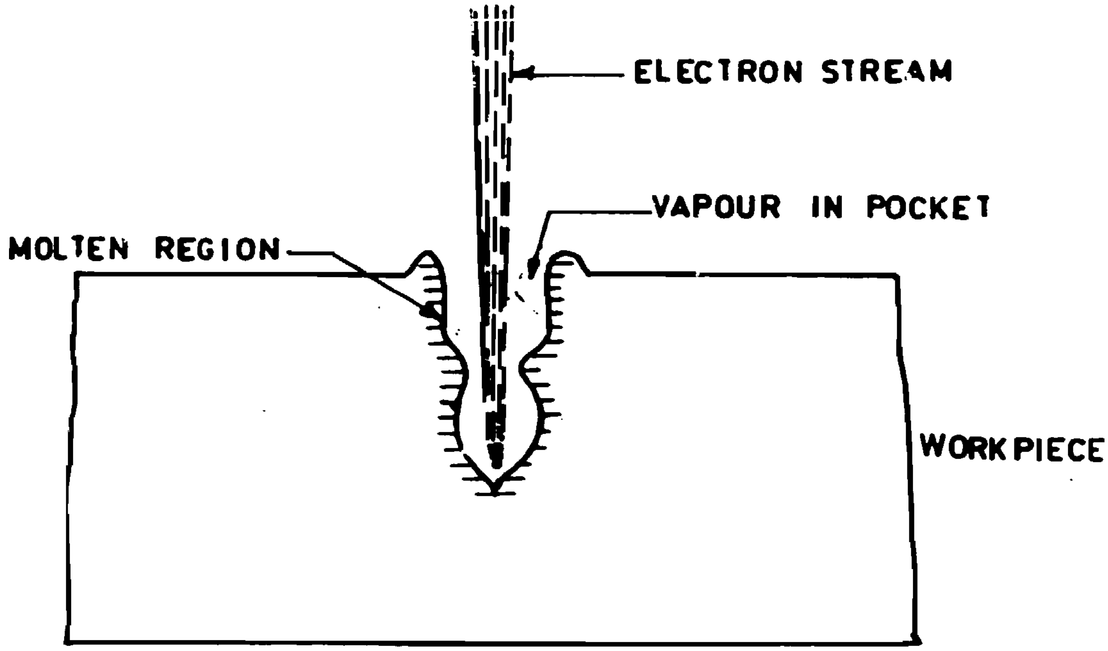

ELECTRON STREAM
VAPOUR IN POCKET
MOLTEN REGION
WORKPIECE

FIG.1

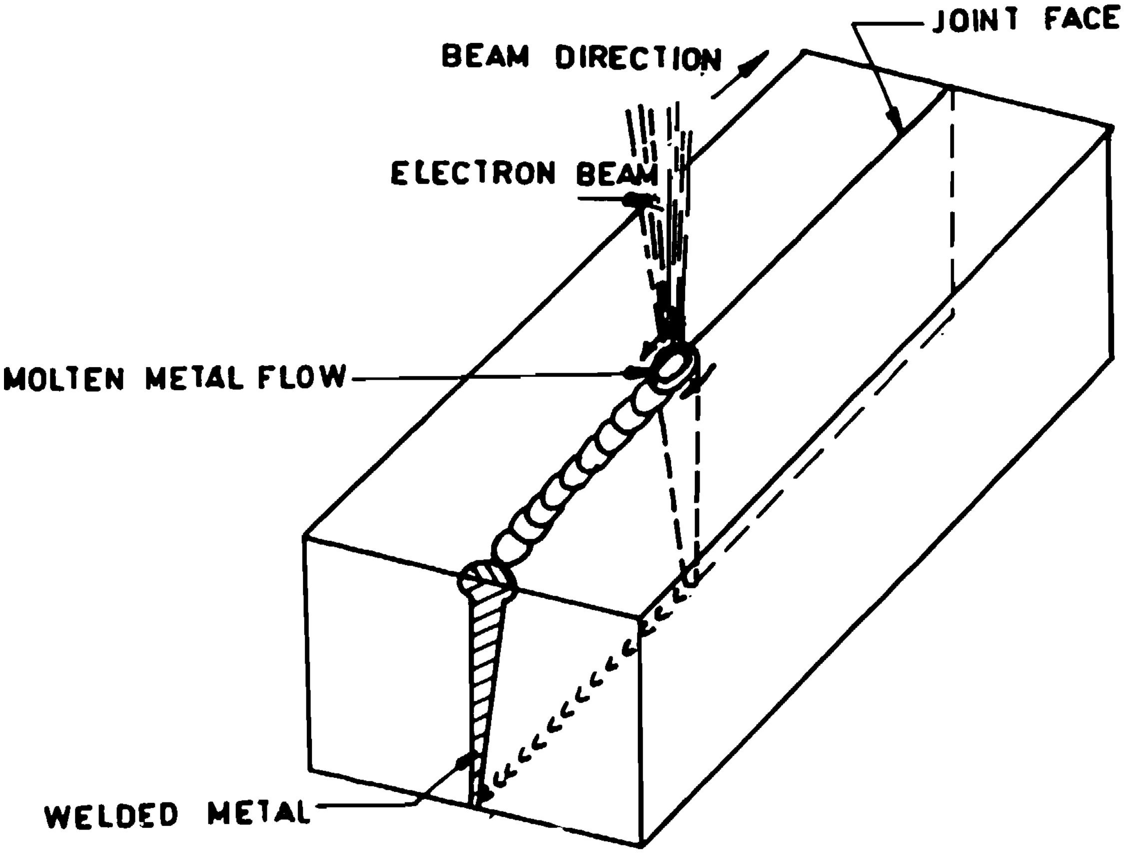

JOINT FACE
BEAM DIRECTION
ELECTRON BEAM
MOLTEN METAL FLOW
WELDED METAL

FIG.2

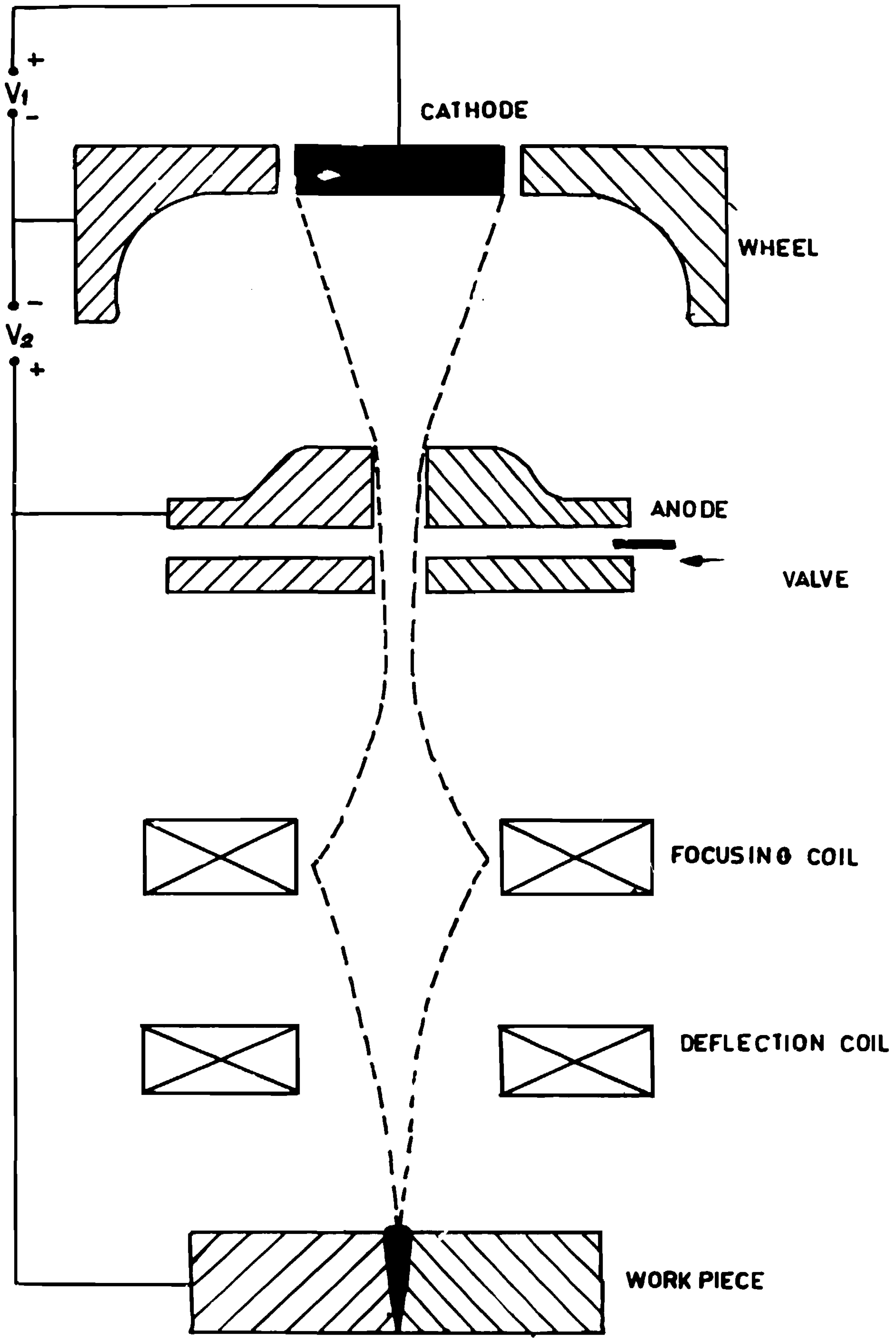

+
V1
-
CATHODE
WHEEL
-
V2
+
ANODE
VALVE
FOCUSING COIL
DEFLECTION COIL
WORK PIECE

FIG. 3

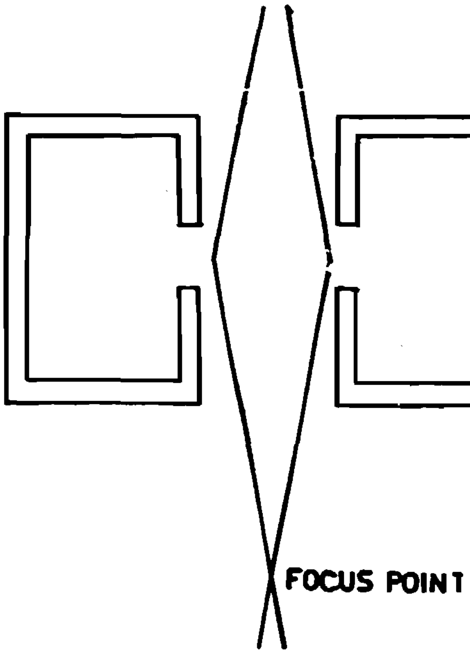


FIG. 4.a.

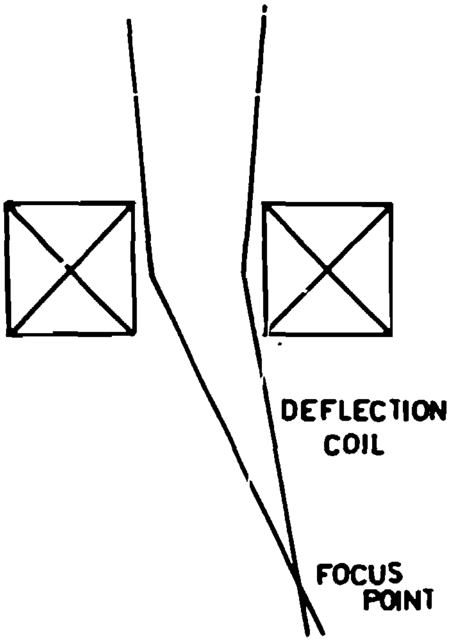


FIG. 5.

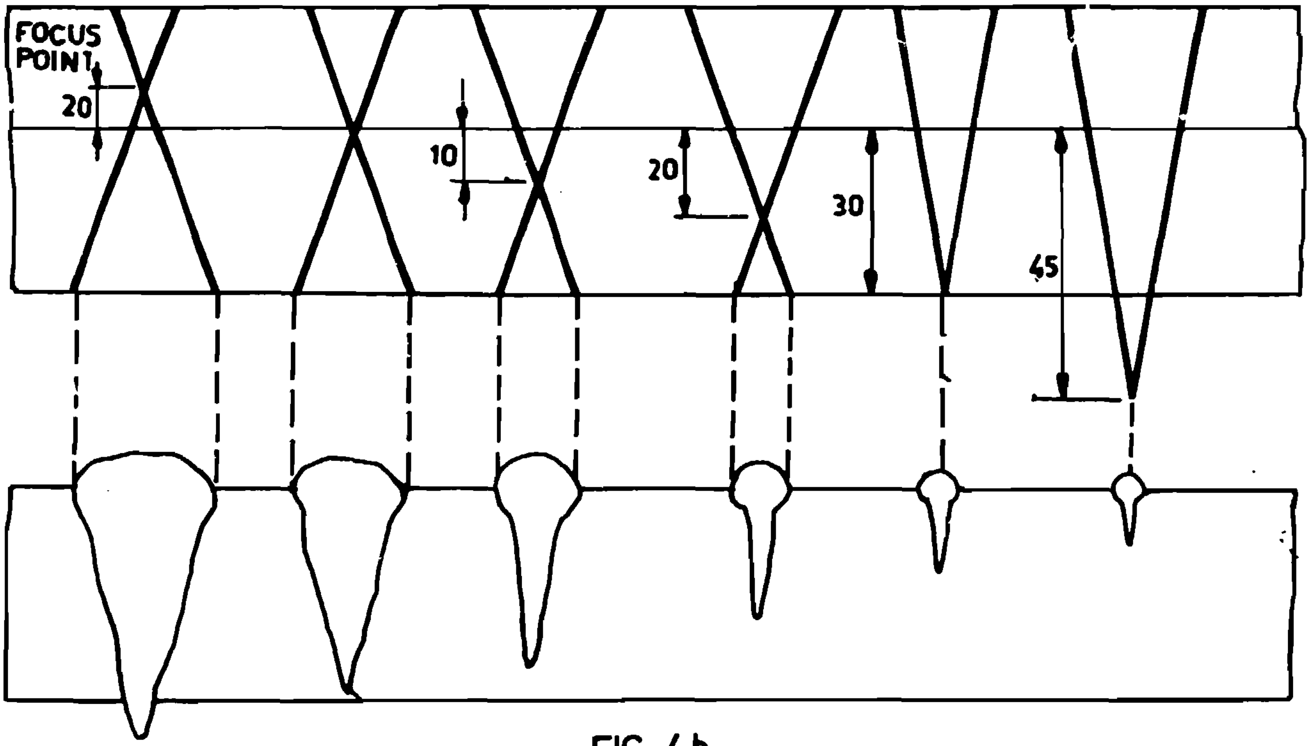


FIG. 4.b.

EFFECT OF THE FOCAL LENGTH ON THE GEOMETRY OF THE BEAD

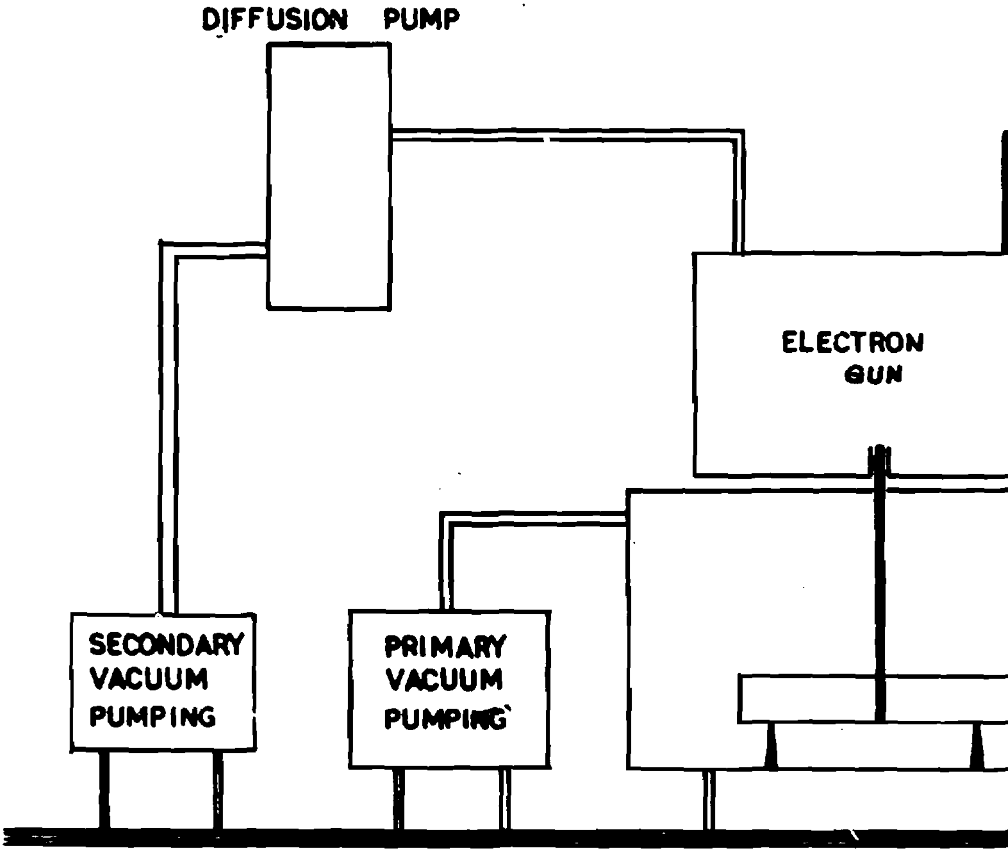
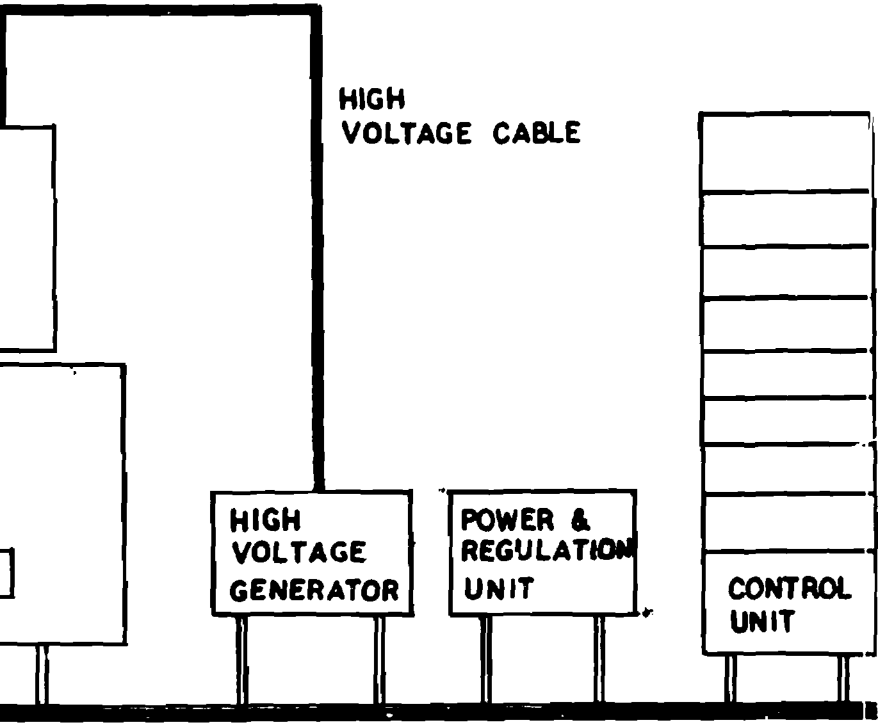

DIFFUSION PUMP
ELECTRON GUN
SECONDARY VACUUM PUMPING
PRIMARY VACUUM PUMPING

FIG 6


HIGH
VOLTAGE CABLE
HIGH
VOLTAGE
GENERATOR
POWER &
REGULATION
UNIT
CONTROL
UNIT

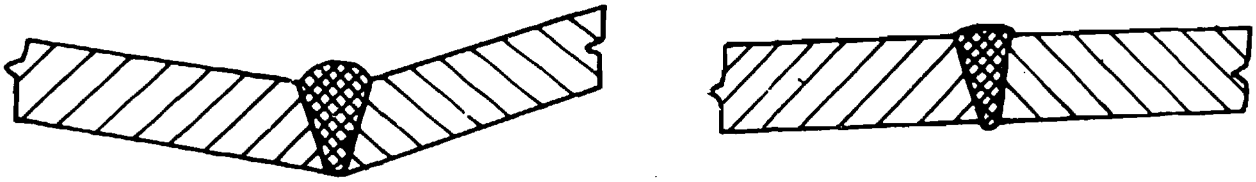


FIG.7.

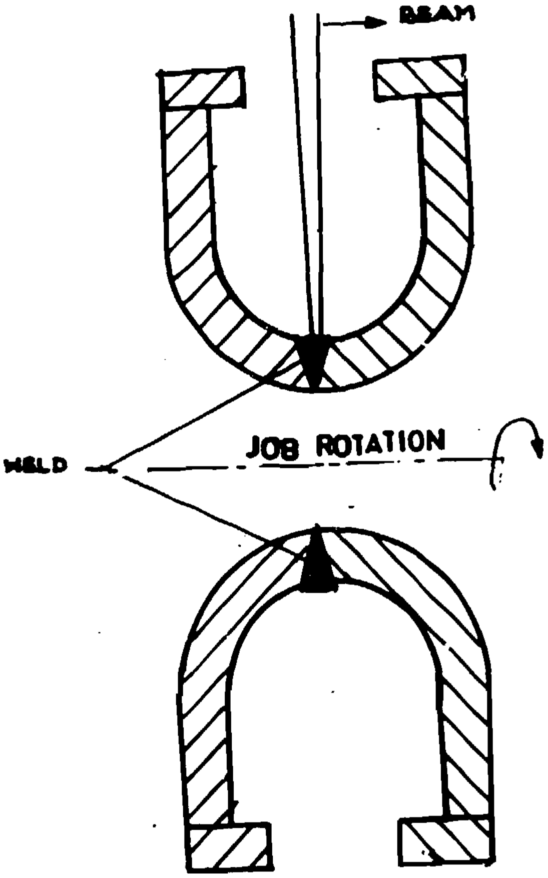


FIG.8

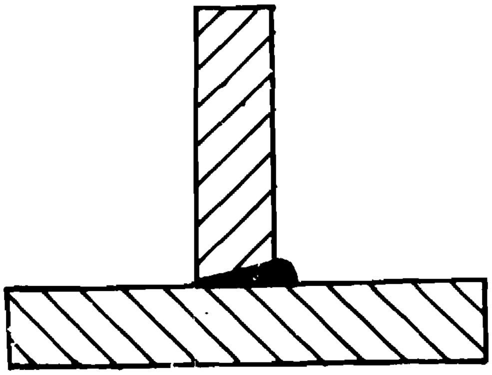


FIG.9

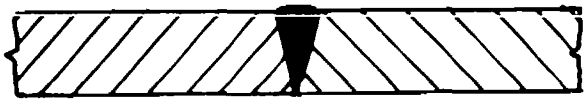


FIG.10

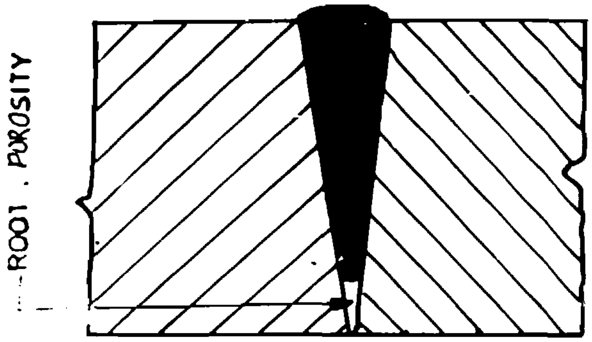


FIG.11

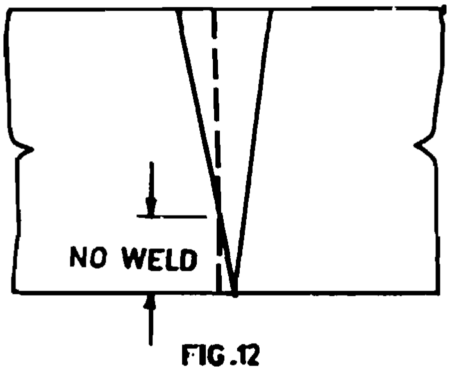


FIG.12

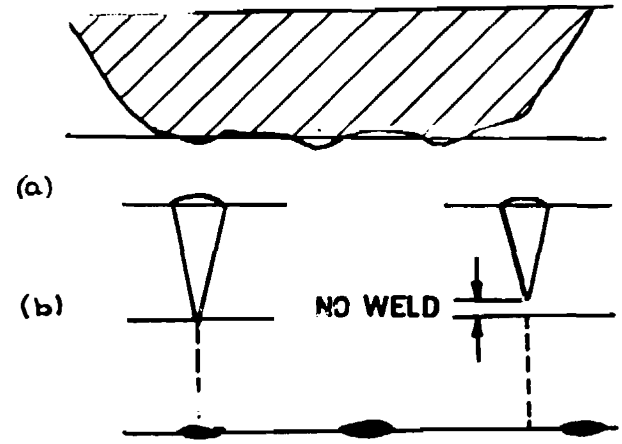


FIG - 13

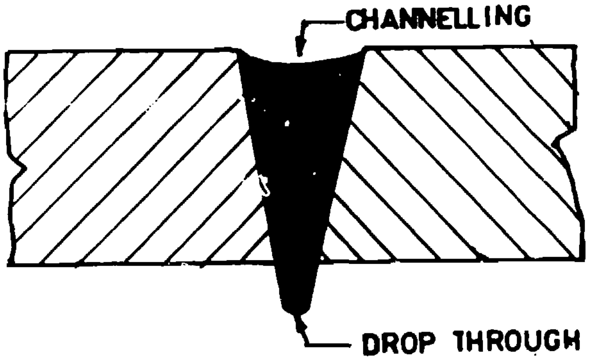
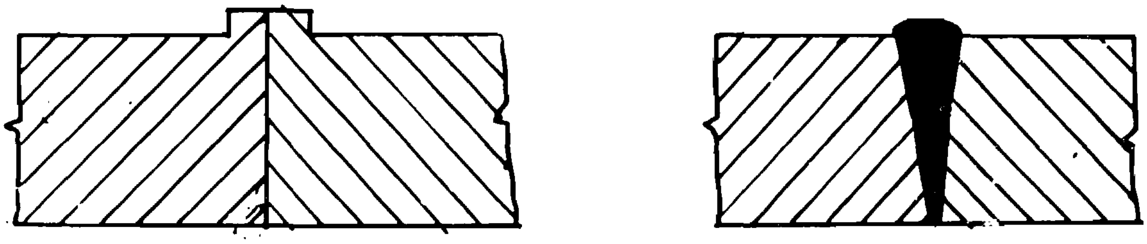


FIG.14



JOINT PREPARATION WITH LIP

AFTER WELD

FIG.15

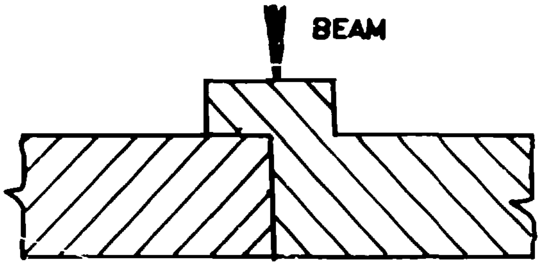
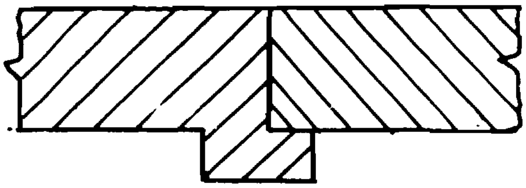


FIG.16



JOINT PREPARATION

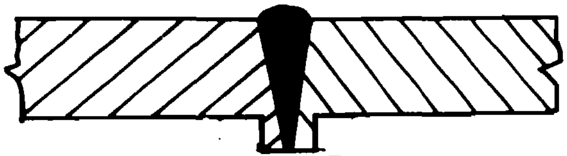
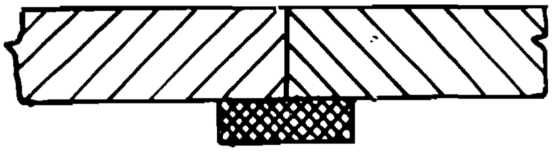


FIG.17



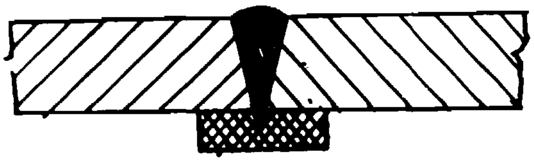


FIG.18

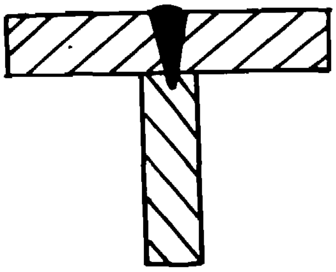


FIG.19

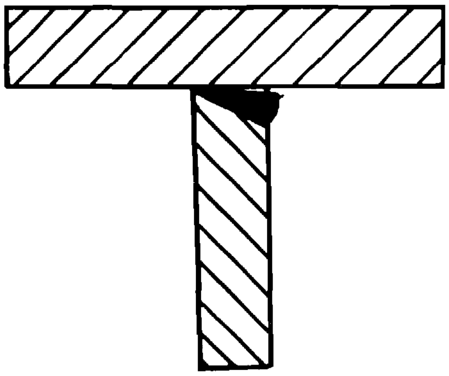


FIG. 20

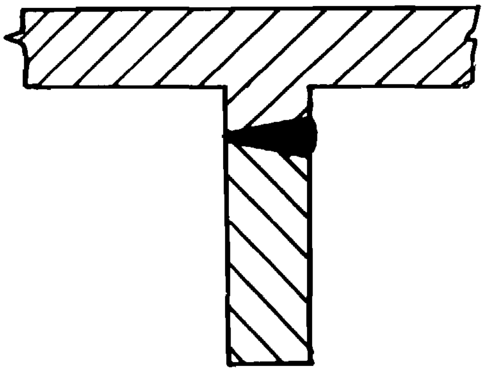


FIG.21

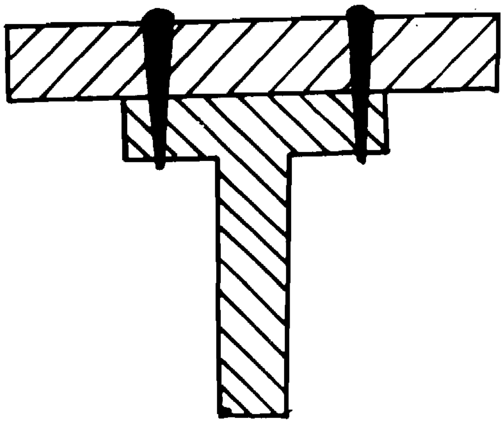


FIG.22

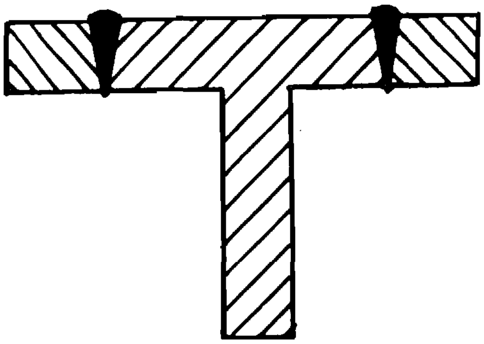
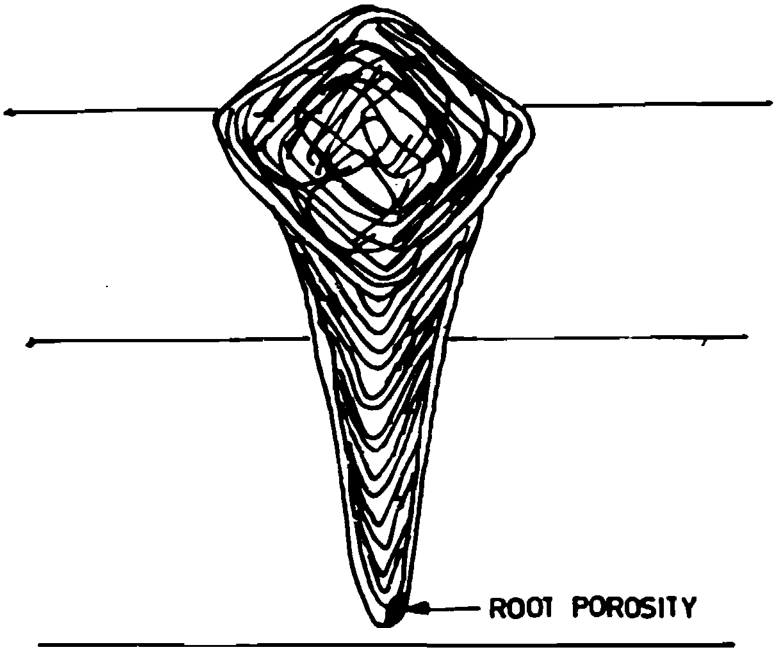
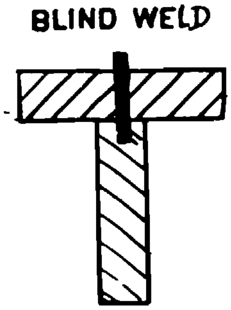


FIG.23





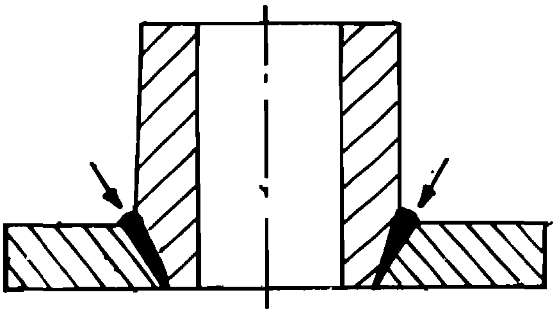


FIG. 24

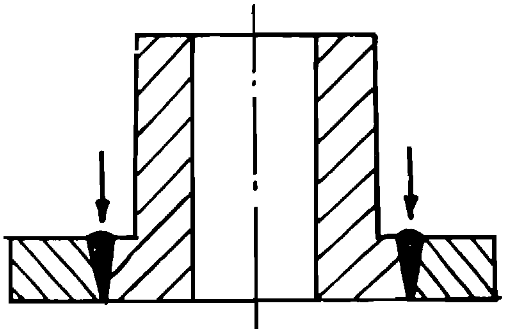


FIG. 25

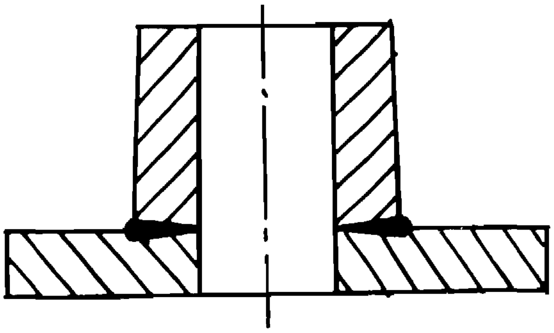


FIG. 26

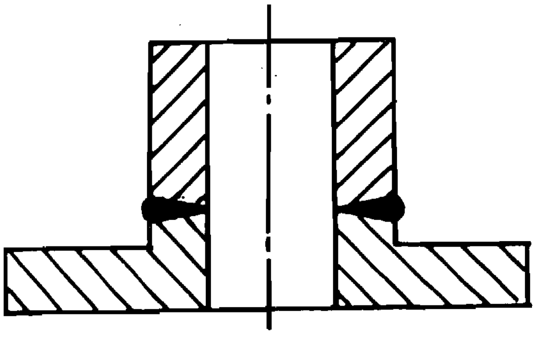


FIG. 27

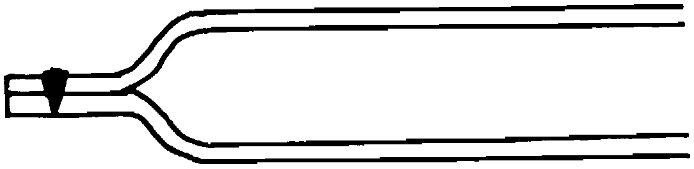


FIG. 28

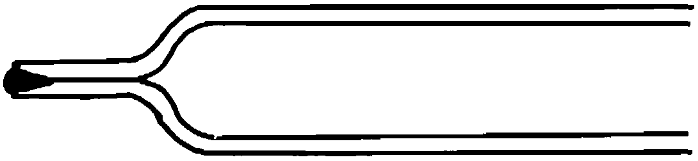


FIG. 29

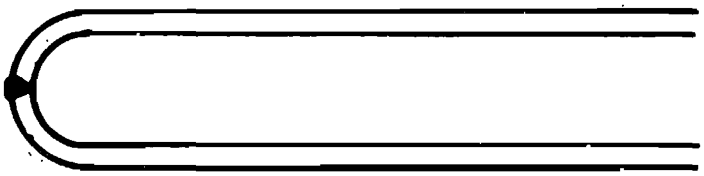


FIG. 30

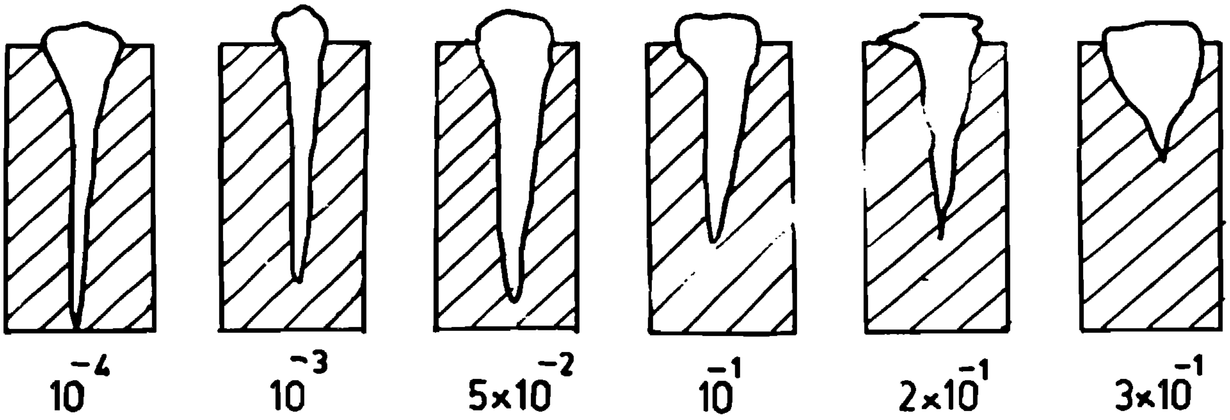


FIG. 31

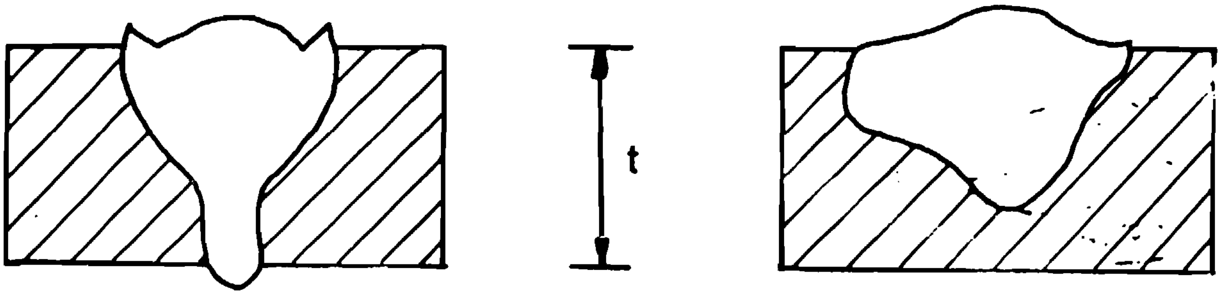
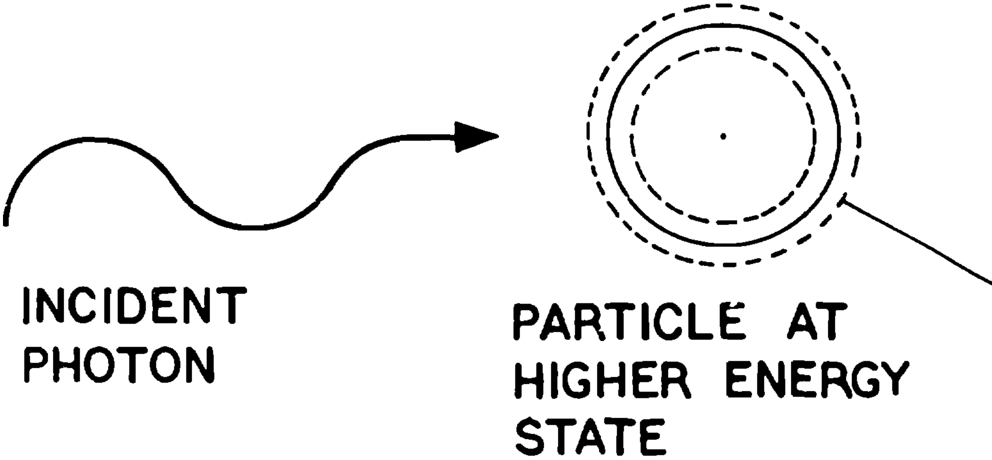
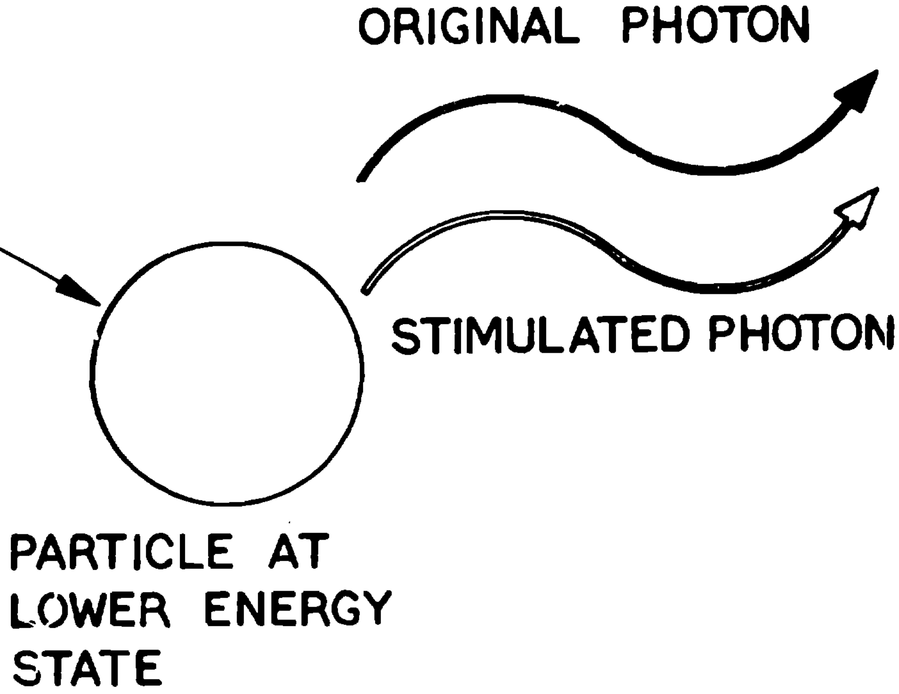


FIG. 32

STIMULATED EMISSION

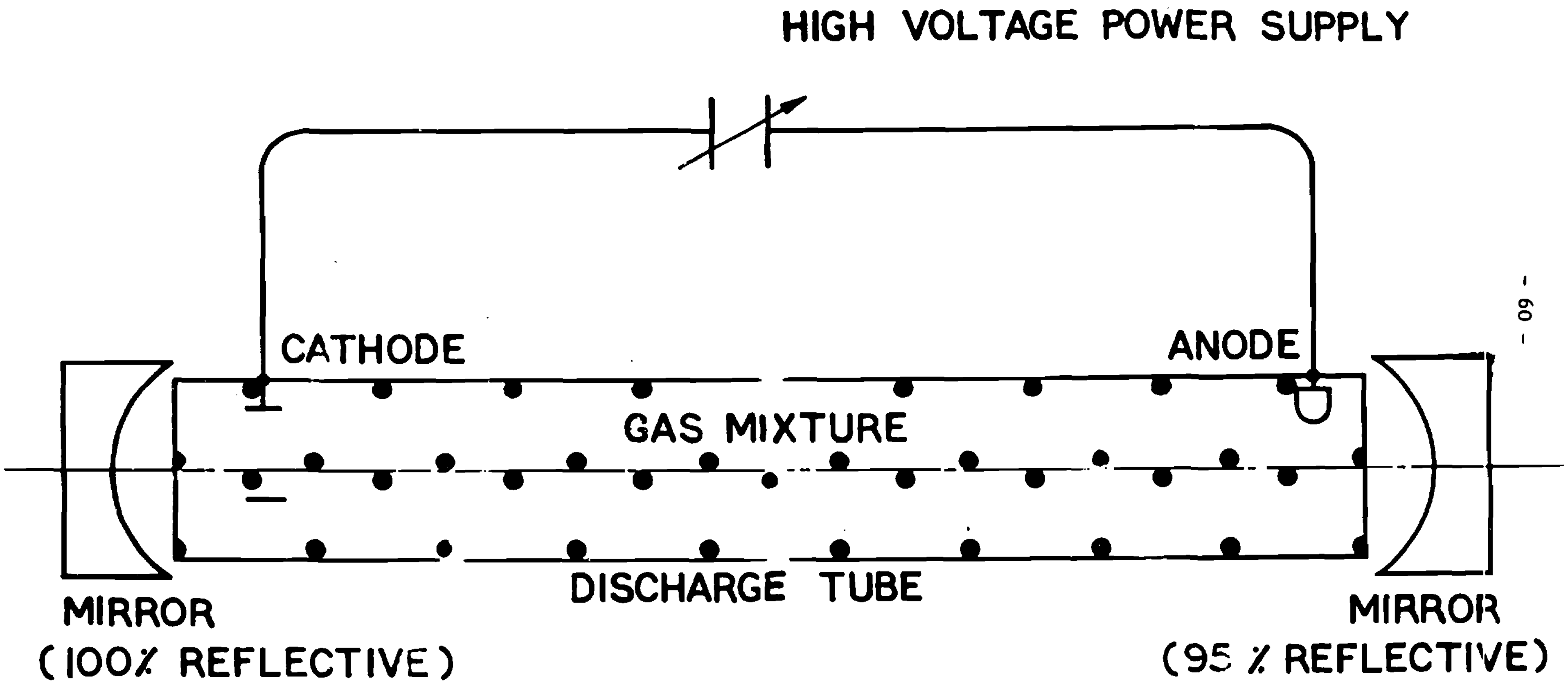
FIGURE 33




ORIGINAL PHOTON
STIMULATED PHOTON
PARTICLE AT LOWER ENERGY STATE

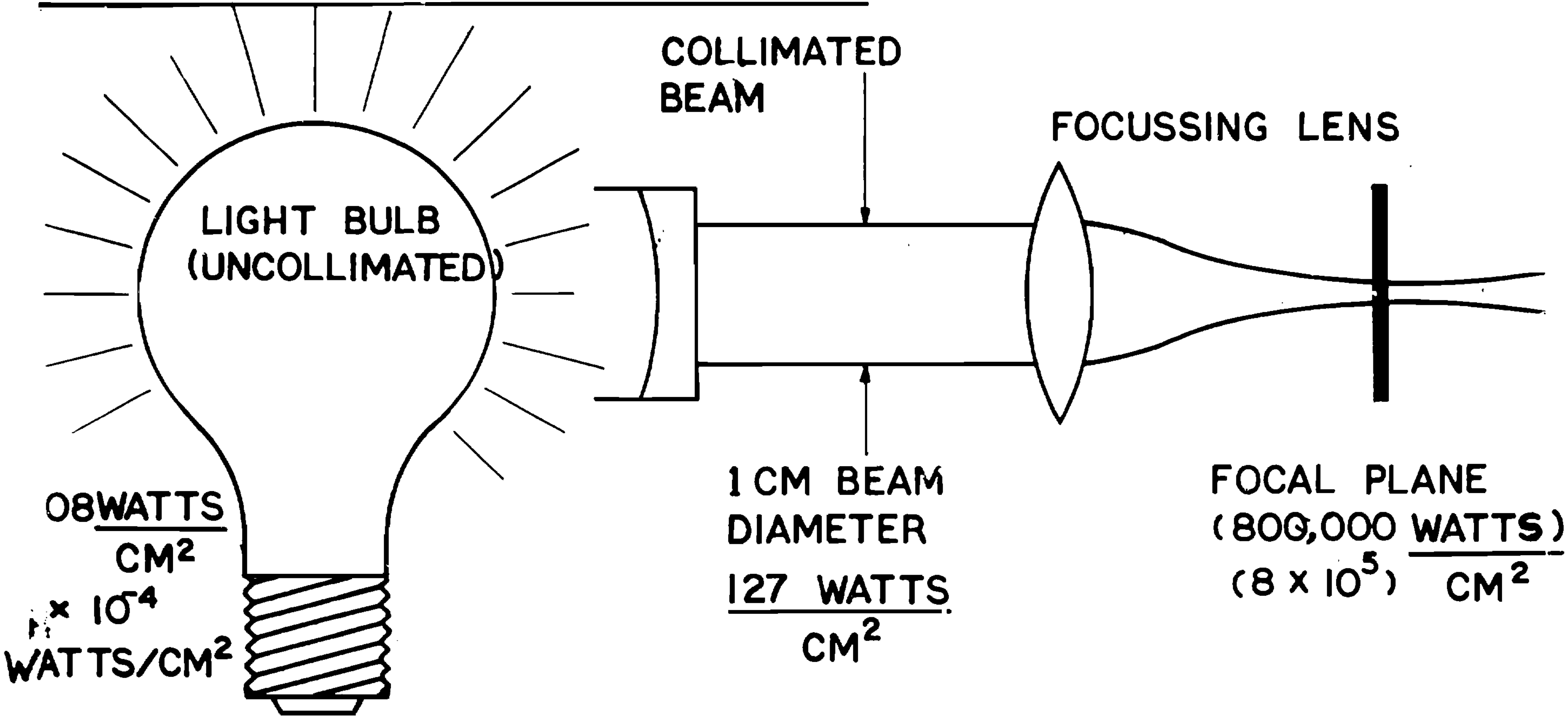
BASIC CO_2 LASER CONFIGURATION

FIGURE 34



SPATIALLY RANDOM VS COLLIMATED LIGHT

FIGURE 35



100 WATTS TOTAL OUTPUT AT A DISTANCE OF ONE METER PROVIDES

POWER DENSITY UNFOCUSSED

100 WATT LESER FOCUSSED TO 0.005 DIAMETER SPOT (0.0126 CM) PROVIDES

POWER DENSITY FOCUSSED

TYPICAL LASER CHARACTERISTICS

FIGURE 36

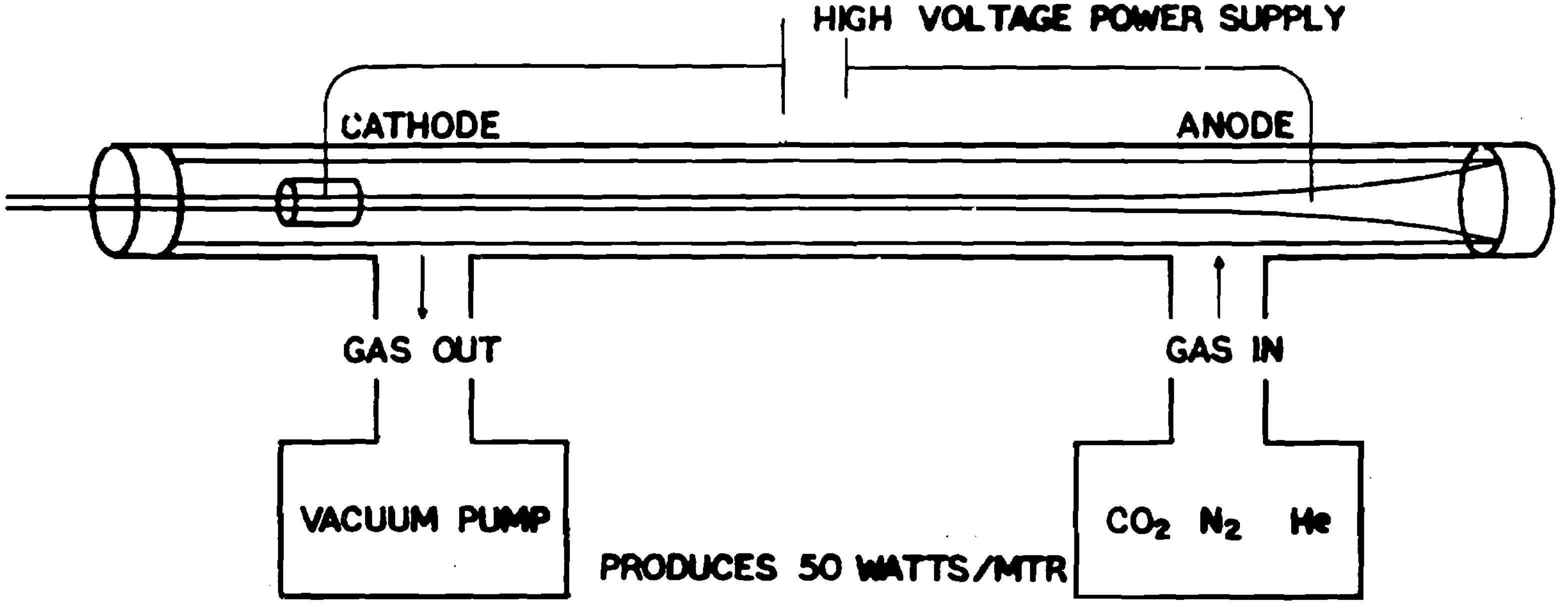
TYPE	WAVE-LENGTH (nm)	OPERATING MODE	MAX. REP. RATE (pps)	PULSE WIDTH	POWER TEM_{00} (watts)	MOLTIMODE
He Ne	632·8	CW	—	—	0·0005 0·015	
Ar	451·9 TO 514·5 488·0 514·5	CW	—	—	20 10	—
CO_2	10·6(μm)	CW	—	—	500	UP TO 100.000 WATTS
	10·6(μm)	PULSED	2500	100 μsec LONGER	—	4,000 FOR 500 CW
CO_2 TEA	≅10·6	PULSED	400	400 μsec	—	100,000
He Cd	325·0	CW	-	—	—	—

TYPICAL LASER CHARACTERISTICS (2)

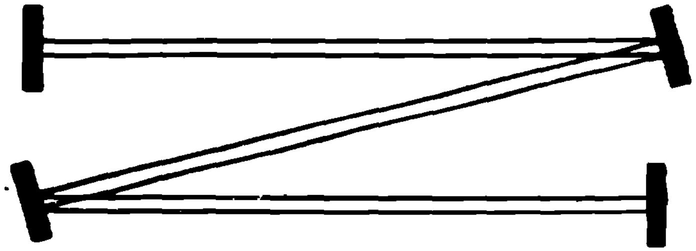
TYPE	WAVE LENGTH (nm)	OPERATING MODE	MAX. REP. RATE (pps)	PULSE WIDTH	POWER TEM$_{00}$ (watts)	MULTIMODE
KRYPTON	350·7 TO 799·3	CW	—	—	6	—
NITROGEN	337·1	PULSED	TO 500	10 μsec		250,000 (2·5 mj)
Nd : GLASS	1·06 (μm)	PULSED	1	500 μsec → 10 msec		10^6 (125 j)
Nd : YAG	1·064 (μm)	CW			20	200
	1·064	PULSED (FLASH-LAMP)	400	100 μsec → 12 msec		400 (20 j)
	1·064	PULSED (A.O.Q. SWITCH)	50,000	200 μsec		50 (5 mj)

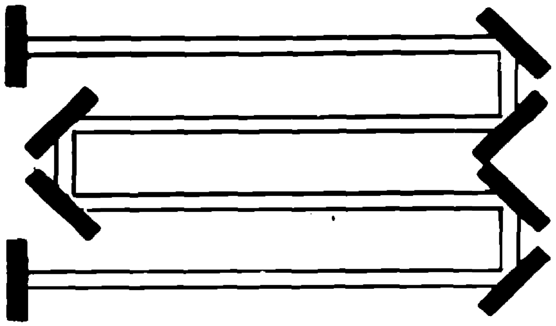
AXIAL-FLOW CO_2 LASER

FIGURE 37



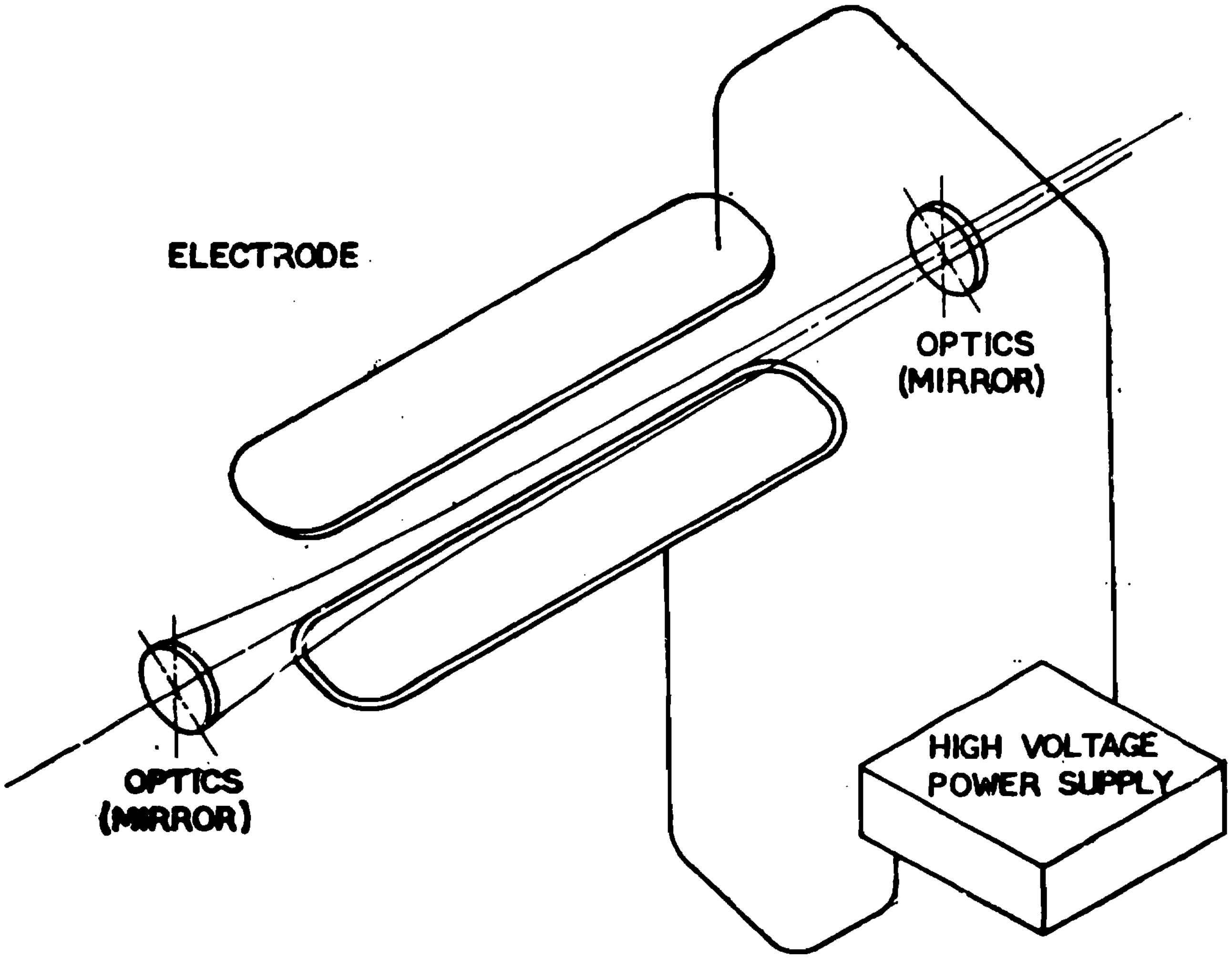
RESONATOR CONFIGURATIONS





TRANSVERSE EXCITED ATMOSPHERIC (TEA) LASER

FIGURE 38



TYPES OF LASERS

FIGURE 39

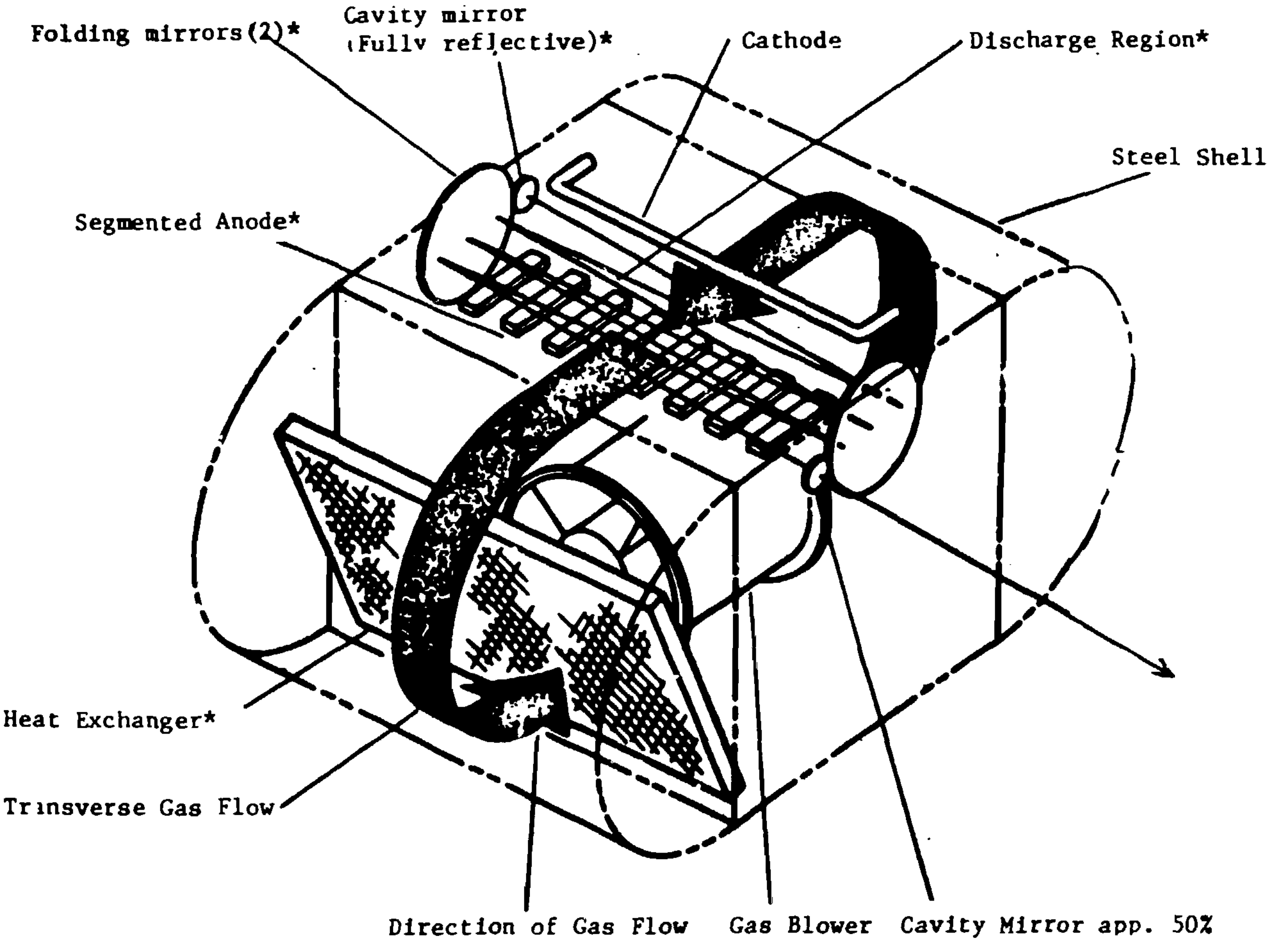


FIGURE 9 GAS TRANSPORT LASER (DRAWING COURTESY OF ELECTRONIC SYSTEMS GROUP, WESTERN DIV., G.T.E. SYLVANIA INC., MOUNTAIN VIEW, CALIF.)

SOLID-STATE LASER

FIGURE 40

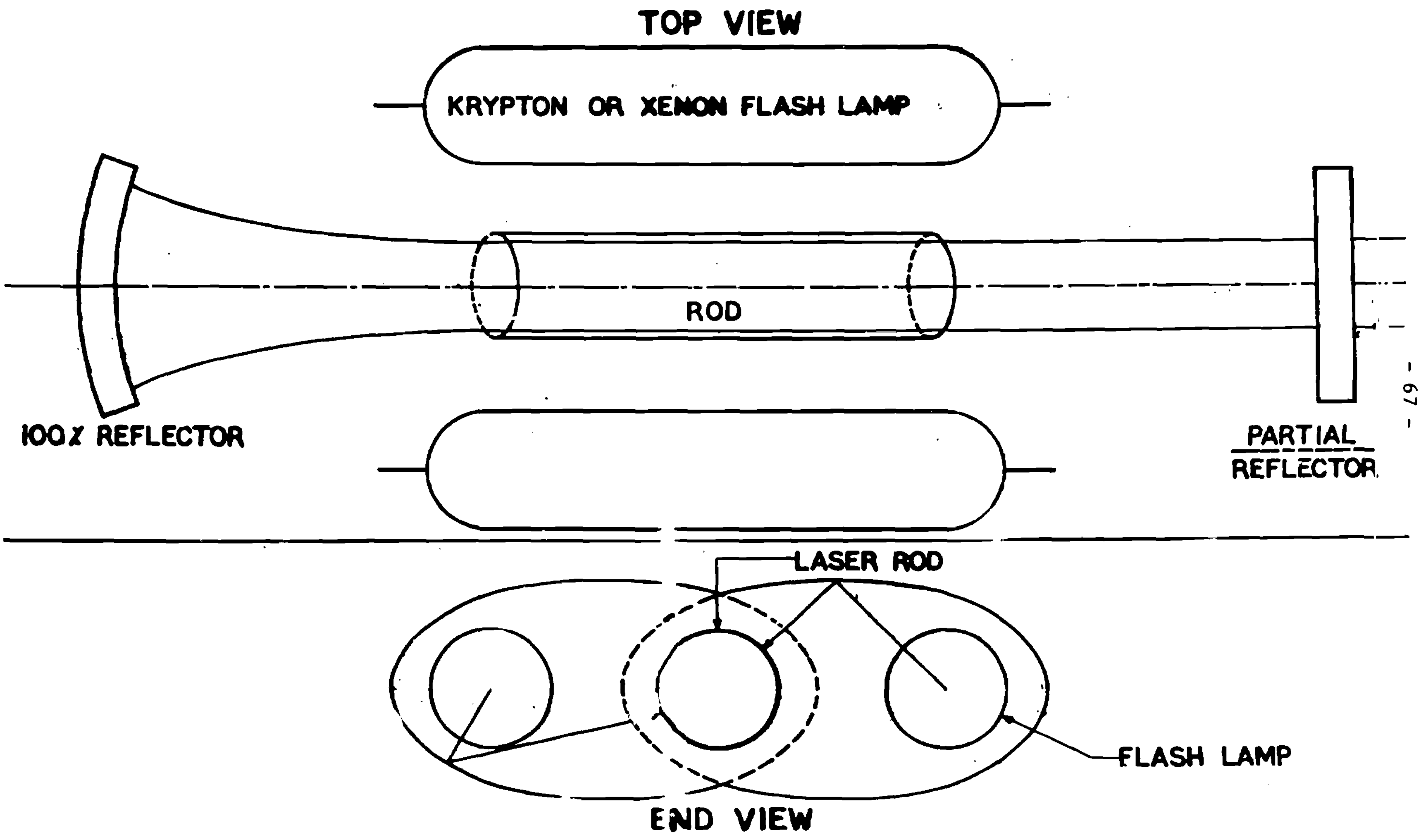
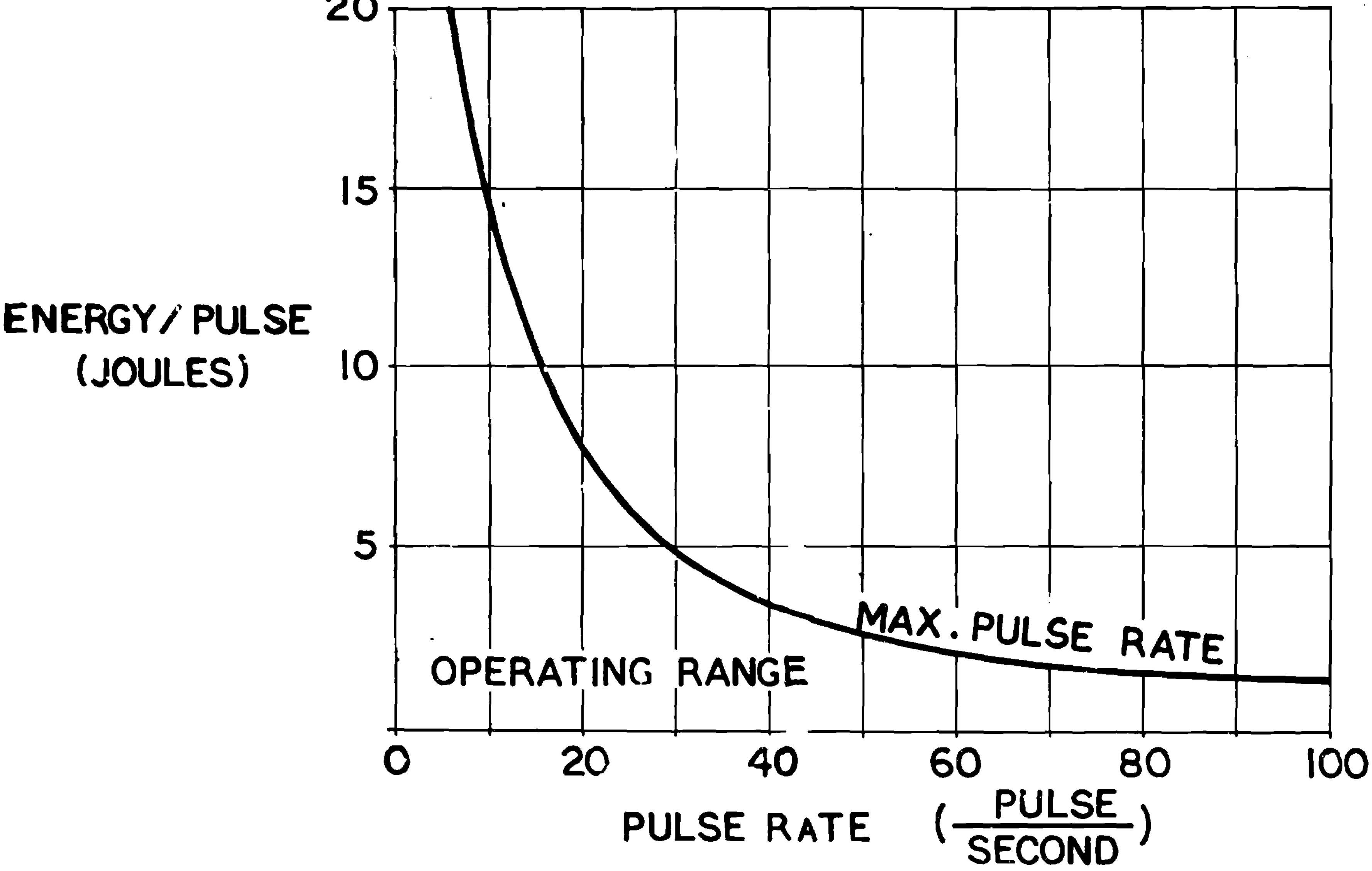


FIGURE 41

FLASH LAMP PULSED Nd:YAG



Q-SWITCHED Nd : YAG LASER

FIGURE 42